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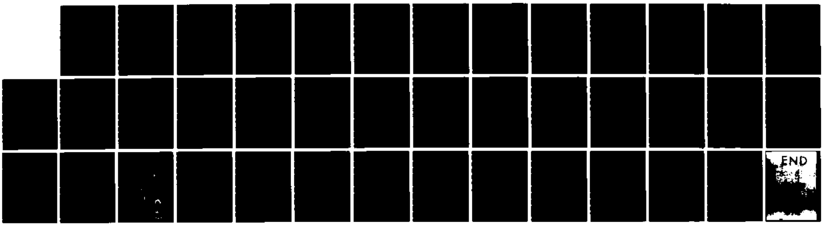

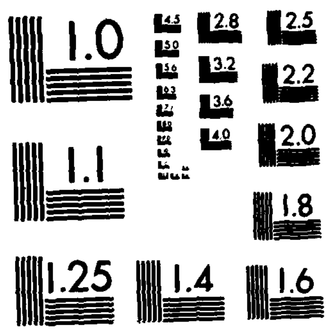

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: N00014-76-C-0004 Final Report
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): ARCTIC PHYSICAL OCEANOGRAPHY
5. TYPE OF REPORT & PERIOD COVERED: FINAL 7/1/75 - 12/31/83
6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Kenneth Hunkins
8. CONTRACT OR GRANT NUMBER(s): N00014-76-C-0004
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Lamont-Doherty Geological Observatory of Columbia University
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Dept. of the Navy, 800 N. Quincy St., Arlington, Va. 22217. Att: Leonard Johnson, Scientific Off. 428AR
12. REPORT DATE: July, 1984
13. NUMBER OF PAGES: Three
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)

See attatched Distribution List.

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Arctic Ocean, Physical Oceanography, Hydrography, Ocean Currents.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The physical oceanography of the Arctic Ocean has been investigated on three different field expeditions: AIDJEX ('75-76), FRAM ('79-82), and MIZEX (1983). The locations of these expeditions cover the range of Arctic Ocean environments from the polar park of the Beaufort Sea to the ice edge in Fram Strait. Meso- and finescale oceanographic structure in these areas was monitored with hydrographic profiles taken from drifting ice stations and at remote sites reached by helicopter. Ocean currents were monitored

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by both profiling and fixed current meters suspended from drifting ice stations.

A bibliography is included of scientific papers and technical reports covering accomplishments under this contract.

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FINAL TECHNICAL REPORT

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U.S. Navy Contract N00014-76-C-0004

ARCTIC PHYSICAL OCEANOGRAPHY

July 1, 1975 - December 31, 1983

* * *

Kenneth Hunkins, Principal Investigator

Lamont-Doherty Geological Observatory
of Columbia University
Palisades, New York 10964

Introduction

Among the oceans of the world, the Arctic Ocean is unique in being covered with ice. In summer, sea ice covers only the central part of the Arctic Ocean but in winter, pack ice expands to cover the entire Arctic Ocean, as well as surrounding seas such as the Bering and Barents. The study of the physical oceanography of arctic seas has been slowed in the past by the difficulties of working through this ice cover. The objective of research under this contract has been description and understanding of the currents and hydrography beneath the ice pack using drifting ice floes as research platforms. Particular emphasis has been placed on fine-scale and mesoscale features such as eddies, fronts and wind-driven motion. Field work under this contract was conducted in conjunction with three expeditions:

(1) Arctic Ice Dynamics Joint Experiment, (AIDJEX), 1975-76,

(2) FRAM I, II, III and IV drifting ice stations, 1979-82,

(3) Marginal Ice Zone Experiment (MIZEX), 1983.

These three expeditions represent a progression in geographical location beginning in the Beaufort Sea with AIDJEX in the mid-1970's, moving across the North Pole to the eastern Arctic Ocean with the FRAM stations in the late 1970's and early 1980's and finally, last year, in the marginal ice zone where the edge of the ice pack fronts on the open waters of the Greenland Sea. There was a common objective in all of these expeditions: the mesoscale and finescale oceanographic structure of the Arctic Ocean. Measurements of currents, as well as the salinity and temperature fields of the upper ocean, were included in all programs.

The AIDJEX measurements were conduced from an array of four drifting ice stations over a period of one year. This provided coverage over an annual cycle for the area enclosed by the 100-km array. This produced the first complete seasonal data on mixed layer behavior beneath pack ice showing the transition from the winter, when brine-induced convection dominates, to summer when runoff of meltwater results in a thin low-salinity surface layer mixed by ice motion. In the AIDJEX pilot experiments, vigorous sub-surface eddies had been detected and in the main AIDJEX program the eddy field was further confirmed and statistics were obtained showing the widespread occurrence of these features in the Beaufort Sea and their important contribution to the total kinetic energy.

With the commencement of the FRAM expeditions in 1979, emphasis shifted to time scales less than annual and to wider coverage in area. A major advance in oceanographic techniques for polar oceans was effected beginning with FRAM I in which helicopters and lightweight portable conductivity-salinity-temperature-depth (CSTD) instruments were used to profile the upper 500 m of the ocean over a wide area with a close spacing of stations. Helicopters were based at each of the FRAM camps, permitting a quasi-synoptic survey to be carried out around the camps to a radius of about 100 miles. The range was extended by the drift of the camps during the five or six weeks of spring operations each year. Surveys were most extensive in 1979 and 1981 from the FRAM I and III camps. From the FRAM expeditions came new understanding of oceanographic condtions in the eastern Arctic north of Fram Strait, the major connection between the Arctic Ocean and the rest of the world ocean. The oceanic front which separates outflowing polar waters from inflowing Atlantic waters was demarcated and the melting rate for the ice above the Atlantic Water was estimated. Mesoscale eddy activity appeared reduced in this area when compared with previous experience in the Beaufort Sea.

The helicopter/CSTD program was continued and expanded during the MIZEX project which began with a pilot program in 1983. The aim of MIZEX was a coordinated study of air-sea-ice interaction across the edge of the ice pack in the Fram Strait region. The Lamont helo/CSTD effort mapped oceanographic structure on the ice side of the margin, while structure on the open water side of the edge was surveyed by other groups using conventional techniques using ships.

These expeditions are summarized in three review papers included here. More details can be found in the references included with the reviews, as well as in references in the bibliography of publications produced under funding from this contract.

Review of the AIDJEX Oceanographic Program

by Kenneth Hunkins

from Sea Ice Processes and Models, Proc. of the Arctic Ice Dynamics Joint Experiment Int'l. Committee on Snow and Ice Symposium," ed. by R. Pritchard, Univ. of Wash. Press, Seattle, 1980.

The presence of energetic eddies with diameters of 10 to 20 km and speeds of up to 1 knot was one of the most striking of these. The 1972 project also stimulated efforts toward quantitatively assessing the drag of ice on the water. This led to such contributions as a momentum integral technique for direct measurement of this drag and to discussion of the drag produced by pressure ridge keels.

The oceanographic program for the main experiment of 1975-6 was designed to insure uniform observations at all four manned stations with supplemental observations at the main camp. Salinity and temperature were monitored with Plessey Model 9040 STD systems. The satellite camp STDs were limited to a depth of 750 m by the winch systems and depth sensors. The main camp was limited to 3000 m depths by the depth sensor. Data were recorded digitally on magnetic tape with Plessey Model 8400 data loggers and also graphically on charts. Casts were taken twice each day to 750 m at all four camps on a synchronized schedule. A weekly cast to 3000 m was made at the main camp. Between casts the sensors were suspended in the steep density gradient at about 60 m to record a time series of fluctuations.

Water velocity was recorded with both fixed and profiling current meter systems. Current meters were rigidly attached to inverted aluminum masts to record currents at each camp at 2 and 30 m, the top and bottom of the planetary boundary layer. Rigid attachment to the ice was used to eliminate the need for a compass in these instruments, always a source of error at high latitudes. The current direction was referenced to ice floe heading which was monitored regularly. A duplicate system of 2 and 30 m current meters was monitored at main camp to determine the effect of local changes in ice conditions on the measurements. The profiling current meters (PCMs) were operated daily at each camp to a nominal depth of 200 m. This was the wire length and the actual depth was always somewhat less than this. These instruments consisted of a Savonius rotor, direction vane and pressure sensor. Direction was referenced to magnetic north.

In retrospect the instruments functioned reasonably well and the basic goals of the project plan were accomplished. The Plessey STDs were a model which our laboratory had used previously and we were prepared for difficulties which might be encountered. However, the Plessey Model 8400 digital data loggers were a new model and we experienced various problems with them. This resulted in some salinity and temperature data being recorded only on paper charts which must be manually digitized later. A Guildline laboratory salinometer was the principle instrument for measuring salinity of samples taken with water bottles. It developed troubles in spring 1975 and was not useable over the summer. A Hytech salinometer provided a backup during this period. The Hydro Product current meters mounted on PVC masts at 2 and 30 m functioned well. Care had to be taken that the mast was not inadvertently rotated and there were some cases when this happened. The TSK profiling current meters were also Savonius rotor and vane types. Their weakness was the rotor system which needed

REVIEW OF THE AIDJEX OCEANOGRAPHIC PROGRAM

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INTRODUCTION

Sea ice, existing at the interface between polar ocean and polar atmosphere, is intimately related to conditions in both the water below and air above. Here we are concerned with oceanographic conditions relating to sea ice motion although effects of the atmosphere will have to be considered at times. The AIDJEX oceanographic program was designed to investigate the Arctic Ocean on a space scale of 100 km in the horizontal direction and hundreds of meters in the vertical. It was specifically directed to revealing oceanographic behavior which directly influences the drift of pack ice. This includes the drag of a quiescent ocean and its variation with changes in stratification, and advection of the ice by currents both transient and steady. Data on salinity, temperature and currents were collected at three stations for a one year period and for about one-half of a year at a fourth station which broke up. These data are still only partially reduced and interpreted. They will be an important source of study for a long time. This data set is unique for the Arctic Ocean and probably for any ocean since detailed investigation of the upper layers in open oceans presents considerable difficulty.

BACKGROUND

From the time of Nansen's drift on the FRAM at the end of the 19th century, which marked the beginning of arctic oceanography, until planning for AIDJEX began in 1969, considerable information was collected on oceanographic parameters in the Arctic Ocean. This information was primarily salinity and temperature observations with classical water bottle and reversing thermometer methods at many locations. This data led to the identification of the primary water masses and gave some idea of their spreading throughout the basin (Coachman and Aagaard, 1974). The Arctic Surface Water, 0 to 50 m, coincides in the winter with the upper mixed layer and is of direct interest to AIDJEX since frictional effects due to ice motion occur primarily in this layer. Water intrudes into the Arctic Basin from both the Atlantic and Pacific sides, spreading horizontally, essentially along surfaces of constant density. The Pacific Water occupies a level between 50 and 200 m in the region of the AIDJEX array and coincides with the region of high kinetic energy with dynamics important to exchange processes. The Atlantic Water, 200 to 900 m, does not appear to be such a high energy region.

Prior to AIDJEX the data taken in different locations were generally not synoptic but the stability of the density field allowed sections from different years to be combined. This led gradually to a knowledge of mean salinity and temperature fields and the general circulation of the water masses. The steady-state density and velocity fields came to be understood on the basin-wide scale. An important addition to knowledge on these scales was made by Worthington (1953) when he identified the clockwise Beaufort gyre which circulates in the area of the AIDJEX array.

Observations of some smaller scale features and transient phenomena were conducted from Fletcher's Ice Island (T-3) and from Station Alpha during the IGY. A number of intriguing oceanographic features were noted. Surface waves were detected in the ice-water system. These were of long period, 10-15 sec., but only millimeters in amplitude (Hunkins, 1962). Internal wave study with thermistor strings was also begun. Current meters of various types were deployed and there were early hints of the swift transient currents at relatively shallow depths. Frictional effects beneath the ice also were investigated from pack ice near T-3 and a spiral behavior of the current vector with depth was seen which closely followed the theoretical behavior predicted by Ekman many years earlier (Hunkins, 1966). There had also been detection of intriguing step structures in temperature in the depth range of 100-500 m (Neshyba et al., 1971).

THE OCEANOGRAPHIC FIELD EXPERIMENTS

In order to better determine scales of time and space for the important motions as well as to test instruments and techniques, several pilot projects preceded the main AIDJEX project. In 1970 and 1971 hydrographic stations and current meter observations were made by the University of Washington group. Current meter profiling was conducted by the Lamont group at the 1971 camp. In 1972 a one month comprehensive pilot project included a main and two satellite camps in a 100 km triangular array from which hydrographic stations were taken (Newton and Coachman, 1973). At the main camp current profiles were taken to 150 m (Hunkins, 1974) continuous current measurements at 10 levels between the surface and 100 m (Hunkins and Fliegel, 1972), and continuous salinity and temperature profiles to 1000 m four times a day and occasionally to the bottom (Amos, 1975). Also on the 1972 pilot project was a unique oceanographic experiment possible only on pack ice. Weber and Erdelyi (1976) measured changes in tilt of sea ice and of the fluid ocean with a hydrostatic level.

The 1972 project showed that the experiments planned for 1975-6 were feasible and pointed directions for improvement of instruments and techniques. The data, although only one month in duration, showed interesting and somewhat unexpected features.

frequent calibration. The fixed Hydro Products instruments at 2 and 30 m depth were used as a standard and the [illegible] was calibrated against the fixed instruments on each cast.

THE OCEANIC BOUNDARY LAYER AND ICE-WATER STRESS

A principal aim of the oceanographic program of AIDJEX was determination of the stress at the water-ice interface. It was expected that for ice movements on a short time scale the ice dragged the water while for long time scales the water dragged the ice. The drag was measured during the 1972 project using a momentum integral method which depends essentially on the quality of observations and does not involve the usual boundary layer assumptions. Hodographs connecting the tips of the current vectors at different depths generally showed a modified Ekman spiral, modified in that the spiral did not exactly match the theoretical one for constant eddy viscosity but did show the characteristic clockwise turning with depth. This general pattern of a modified Ekman spiral in the uppermost layers has also been often observed in the main experiment (fig. 1).

The maximum 12-hour mean wind speed observed during the month of observations in 1972 was 10.0 m/s. This is equivalent to a wind stress of 1.9 dynes/cm^2. The corresponding water stress measured by the momentum integral technique was 1.1 dynes/cm^2. The results in 1972 indicated that the pressure-gradient force was negligible on the ice on a short time scale but that the wind, water, Coriolis and internal ice stress were all of comparable magnitude. It might be expected that over longer time scales the pressure-gradient force might increase in importance.

One of the objectives is to provide numerical modeling with a useful drag coefficient. It was shown that, on the basis of the 1972 data, the geostrophic drag coefficient might be a useful concept for numerical models and that the Arctic Ocean data scaled with results from other areas (Hunkins, 1975).

A question of importance is the drag effect of large keels which protrude deep into the mixed layer or even through it. Inconclusive attempts were made to settle the question by theoretical and tank model arguments. Rigby (1974) concluded that the pressure or form drag of keels due to production of internal waves might be of importance, especially in summer when the upper layers are stratified. Hunkins (1974) rescaled tank experiment data measured by Ekman over 60 years earlier. Ekman's experiments were directed to an early observation of internal wave drag when the FRAM was slowed unusually in a highly stratified situation off the Siberian coast with nearly fresh water over ocean water. Hunkins concluded that internal wave drag of large keels was unlikely to be important. Direct experiments on the question were performed by Rigby during the main experiment but the results do not seem to have been conclusive.

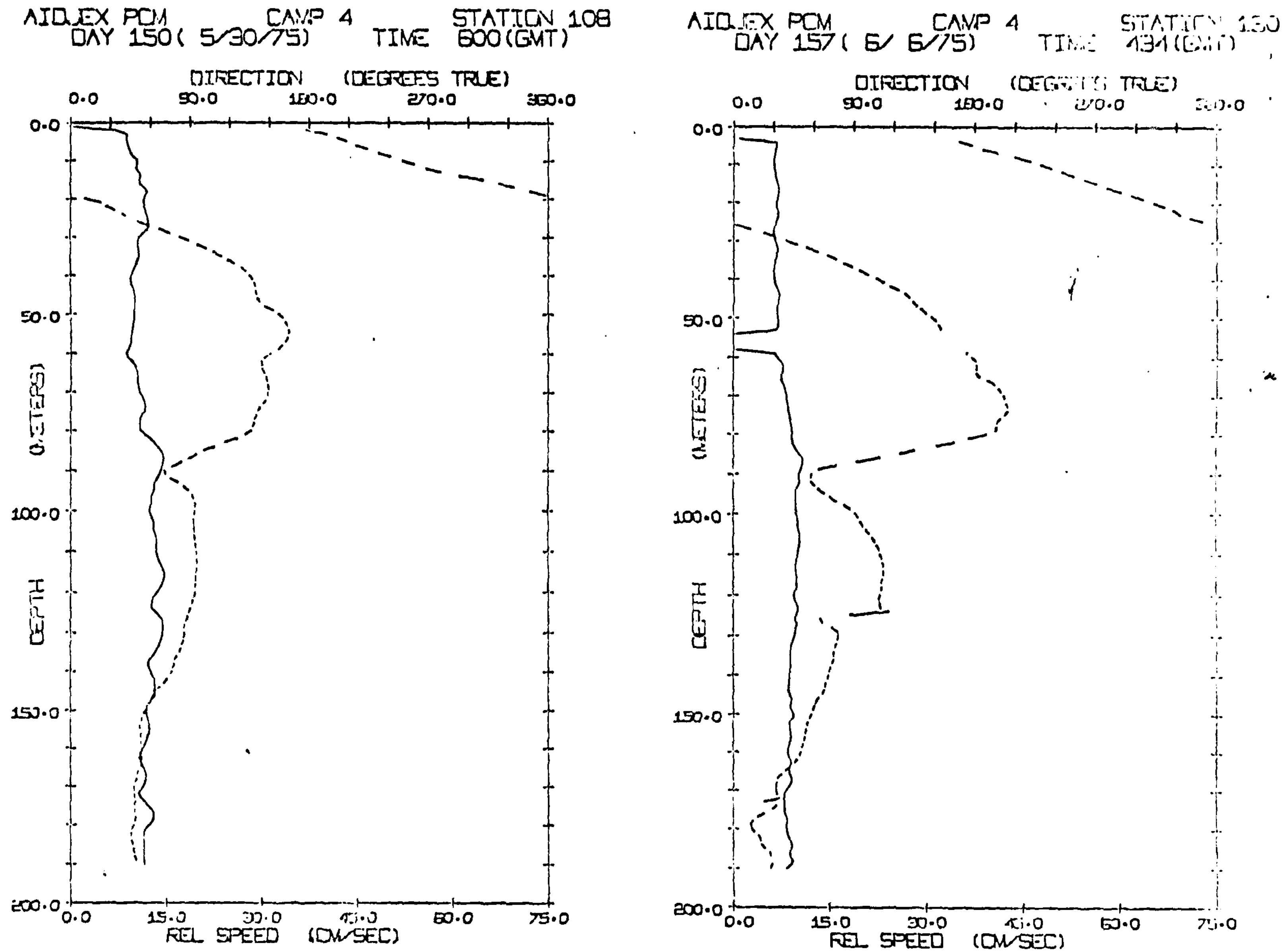


Fig. 1 - Current profiles at Big Bear camp.

MIXED LAYER BEHAVIOR

The mixed layer which appears so strikingly in wintertime arctic profiles of temperature and salinity is attributed to brine convection (fig. 2). Heavy brine is released during freezing to sink down to or below its level of equivalent density, overturning and mixing the surface layers as it descends. Most arctic oceanographic stations were taken in winter and spring months. The mixed layer was recognizable generally in bottle and thermometer casts although details of its structure and evolution were not available. In the 1972 experiment, the mixed layer was about 35 m deep with a sharp break at that level to a steep gradient in temperature and salinity. The continuous record of the Guildline CTD showed the upper 15 m to be often unstable within the resolution of the instruments. The region from 15 to 35 m while still having the appearance of a mixed layer was neutral or slightly stable (Smith, 1974).

Results from the 1975-6 experiment with Plessey STDs show that the mixed layer often has slight steps and that the details of the structure are not coherent over the 100 km array. The mixed layer in the spring of 1975 was about 50 m deep. The small steps in the mixed layer may be due to strong brine convection beneath a refreezing lead.

Fluid dynamical arguments suggest that such steps are limited to a horizontal extent of about 2 kilometers. Their horizontal spread is limited to approximately the Rossby radium of deformation which is small for such small density differences as these steps in the mixed layer (Stommel, 1969).

There are two principle stirring mechanisms by which a mixed layer may be formed: gravitational convection and mechanical stirring. Although the gravitational convection due to brine extrusion during freezing is usually considered most important, mechanical stirring by ice drift must also play some part. Previous studies have not conclusively shown the relative importance of the two regimes (Solomon, 1973). The AIDJEX data should help settle the question when they are more thoroughly studied. The two mechanisms should operate on clearly separated horizontal scales with mechanical stirring by drift occurring over the 1000 km scale of the wind field and brine convection occurring over the 1 to 10 km scale of leads.

Few summertime observations were available on the upper layers before 1975. The AIDJEX records show that a continuous steep gradient in temperature and salinity often exists beneath the ice during summer when freshwater runoff from melting ice and snow stratifies the upper layers. A shallow mixed layer forms when the first freezing develops and is about 15 m deep in September. It deepens slowly, reaching 20 m in December and then continues deepening to reach 40 or 50 m by April.

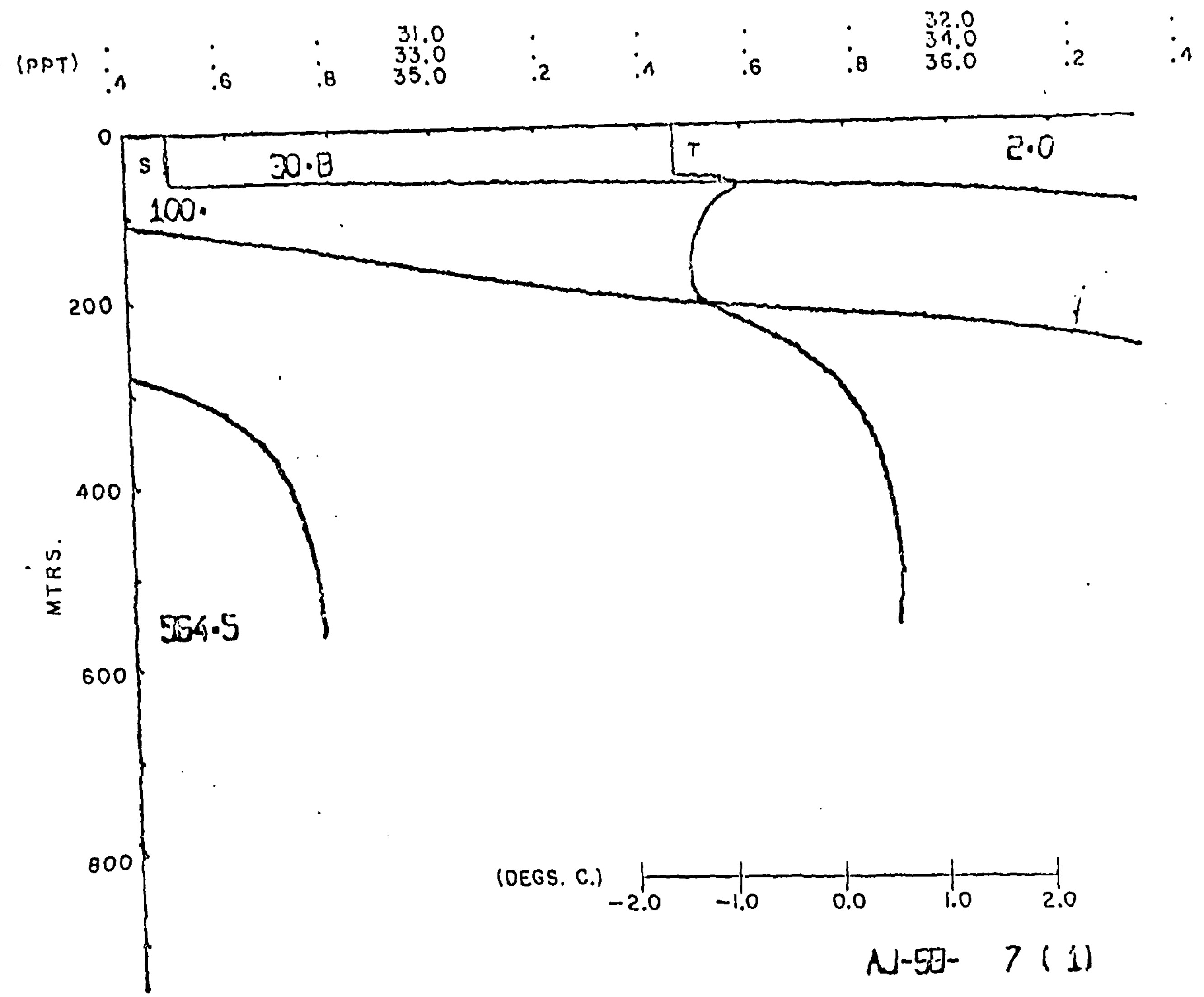


Fig. 2 - Temperature and salinity profile at Snowbird camp.

WIND-DRIVEN FLOW

Wind fields over pack ice change with the synoptic meteorological cycle of a few days. The changes are usually smooth but frontal activity exists and sometimes quite sharp changes are observed. The ice responds to the wind and the water in turn responds to the ice motion. It has become apparent from the 1975-6 data that the ocean tends to respond barotropically to these short term wind changes. The currents are roughly of the same speed as the ice and roughly the same direction. They do not change greatly with depth. The observations extend only to 200 m but go through a region of sharp density change. This suggests that they are barotropic and may extend to large depths.

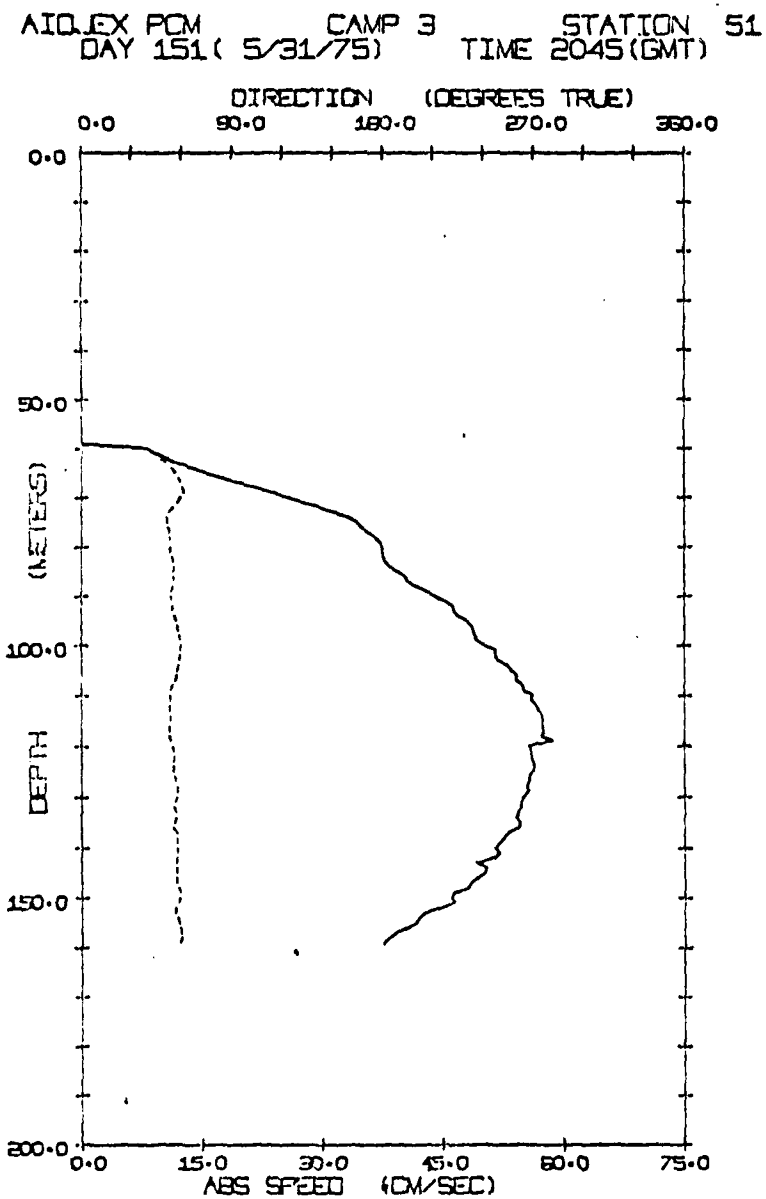
BAROCLINIC EDDIES

One of the unexpected oceanographic results of the 1972 AIDJEX program was the detection of swift subsurface currents localized in the pycnocline. These currents coincided with the region of steepest density gradient between 50 and 300 m. Maximum speeds, found at a depth of about 150 m, reached 40 cm/s. This speed far exceeded the mean current of 1.8 cm/s (Hunkins, 1974; Newton, 1973; Newton et al., 1974).

Although there had been indications of transient undercurrents by P. P. Shirshov as early as 1937 (Belyakov, 1972), the details and horizontal extent were not known. In 1972, these transient currents were shown to occur as nearly circular eddies with diameters of 10 to 20 km. Individual eddies were separated by a spacing of 20 to 50 km. Both cyclonic and anticyclonic circulation were observed. The eddies are strongly baroclinic with signatures in both the velocity and density fields. The force balance is nearly geostrophic although centrifugal force is also of some significance since the eddies have such a small radius.

The detection of subsurfac e eddies provides a new dimension to the energy balance in the Arctic Ocean. Most of the kinetic energy is contained in these eddies rather than in the mean current. For example, in the upper mixed layer the kinetic energy was 7 ergs/cm^3 while at 100 km near the maximum eddy velocity it was 63 ergs/cm^3, nearly an order of magnitude greater.

In the main experiment of 1975-6 eddies were detected at all four camps. Examples of current velocity profiles through eddies at two camps are shown in fig. 3. They differ from the barotropic wind-driven motions by often occurring when there is little ice motion and by their strong vertical shear. The maximum speed was found at 150 m in 1972 but in 1975-6 speed maxima were often somewhat shallower. Current speeds of over 60 cm/s were observed in 1975-6.



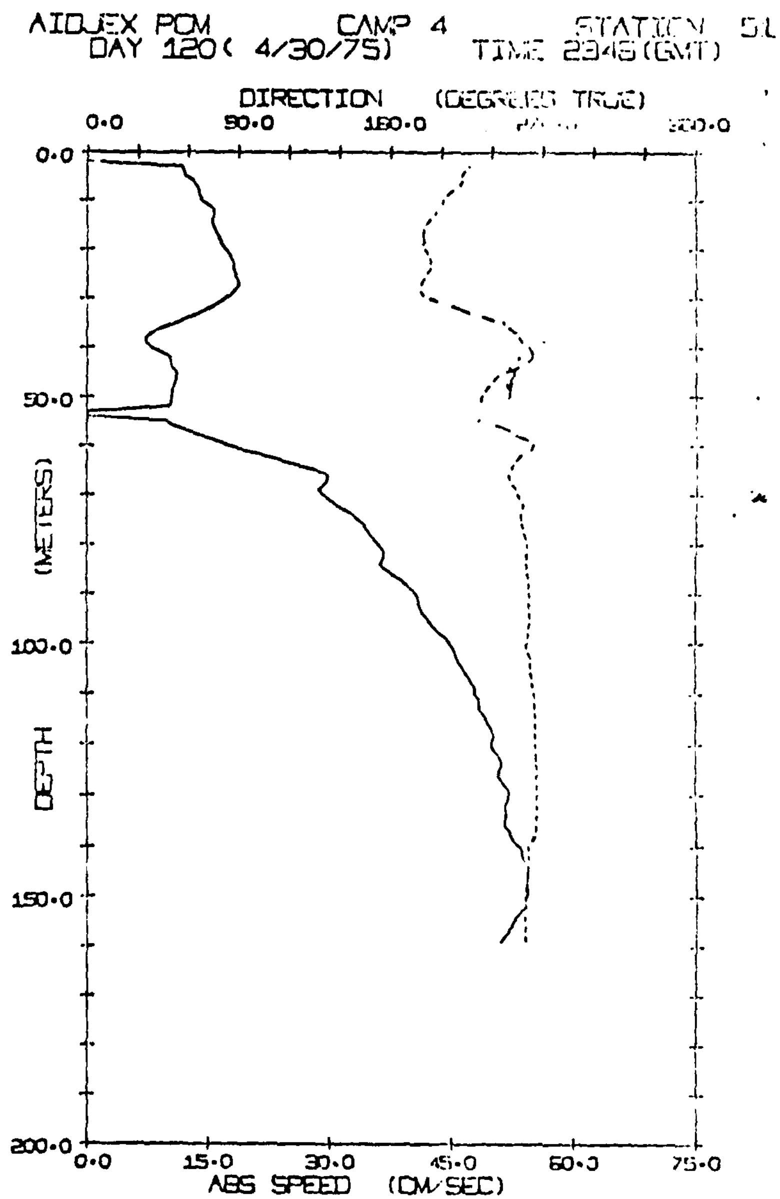


Fig. 3 - Current profiles at Snowbird and Big Bear camps.

Measurements with increased time and space resolution have resulted in detection of baroclinic eddies in the Atlantic Ocean where they have been the object of detailed study during the United Stated MODE experiments and Soviet POLYGON experiments. The arctic eddies differ from the atlantic ones in two ways. The horizontal and vertical space scales of the arctic eddies are much smaller respectively, 20 km and 200 m, than those in the atlantic, 100 km and 4,000 m. This may be related to the steeper and shallower pycnocline in the Arctic Ocean. The depth of maximum velocity also differs between the two oceans. Whereas, in the Atlantic it is presumably at the surface, although data on this is not definite, in the Arctic the maximum is definitely below the surface at 60 to 150 m. This appears related to the presence of the ice cover against which the eddy is frictionally dissipated. Thus the Arctic eddies enlarge the types of conditions under which eddies are known to exist. The prevalence and energy of eddy motion has led to a change in ideas of ocean circulation. Earlier ideas were of a mean circulation disturbed only by small perturbations. The overwhelming contribution of eddies to the energetics of the ocean now require a reassessment of these ideas.

EDDY GENERATION

Some comment and speculation on the possible origins and effects of these energetic features is needed. One of the first steps is to examine the correlation between temperature and salinity within the eddy to see if it agrees with that in surrounding waters. Newton et al. (1974) found the evidence supported a distant origin although Hunkins(1974) found the evidence inconclusive.

The only serious proposal for a mechanism of generation so far seems to be connected with the instability of vertical shear in a stratified fluid under certain conditions. This mechanism is essentially the same as that used to explain the breakup of the mean westerly winds in the atmosphere into the familiar cyclones and anticyclones. There is a basic shear of 2 or 3 cm/sec across the pycnocline in this part of the Arctic Ocean. Calculations show that this is unstable but with growth periods of many months. The growth period is the time taken for an infinitesimal disturbance to grow by a factor of e. Growth is maximum for certain intermediate wavelengths which are on the order of the Rossby radius of deformation. Since the Rossby radius is 10 to 20 km in the Arctic Ocean, depending on the details of how it is calculated, the baroclinic instability origin is a reasonable candidate. The slow growth rate in the AIDJEX area and more favorable growth conditions near the Alaskan Continental Slope suggested to Hunkins (1974) and Hart and Killworth (1976) that they might be generated there and advected north to the AIDJEX area. The effect of the bottom slope, enhanced shear and lack of summer ice cover there all favor instability in the Alaskan Continental Slope region.

The subsurface speed maximum is one of the unique features of arctic eddies which is apparently not found in open ocean eddies. Frictional dissipation against the ice cover is the most likely cause of the decrease in velocity near the surface. Simple theories of baroclinic instability yield disturbance velocity fields with a maximum at the surface if exponential mean density and mean velocity fields are introduced. Exponential mean fields model arctic conditions fairly well. The presence of the ice cover does not change the vertical profile, only decreasing the growth rate and shifting it to a longer wavelength. It is plausible that ~~the~~ eddies are generated in open water near the Alaskan Continental Shelf in summer. They then are carried under the ice pack with the mean current. Once under the ice the velocity at the surface is slowed by the ice. The water in the mixed layer must be quickly slowed by the Ekman spin-down process in which momentum is spread quickly by secondary circulations throughout the layer. The response time for Ekman spin-down is in the neighborhood of one day. The highly stratified layers below the mixed layer will lose their momentum much more slowly. If the stratification is great enough no secondary circulation develops and momentum is lost by diffusion alone. In this case a simple model may be developed for the eddy behavior below the mixed layer showing the deepening and decay of the eddy maximum with time. The diffusive response time is of the order $\tau_d \sim H^2/K$ for eddy diffusion to attain a depth H. H is the depth below the mixed layer of the velocity maximum. The eddy diffusion coefficient, K, is an unknown parameter which must ultimately be determined by observations. There is however some information on the size of K from measurements in other oceans. It might typically be in the area of 1 to 10 cm^2/s in a steep pycnocline such as the arctic one. For K = 1 and H = 100 m, $\tau_d \sim 3$ yrs; while for K = 10, $\tau_d \sim 100$ days. Thus the time taken for the eddies to reach their observed form is on the order of months to years according to these ideas. It would be possible to test this if an eddy could be identified and followed for a long enough time. It may be possible to do this with the 1975-6 data where the same eddies may have been detected at different camps at different times. However, the coarse array was not designed for tracking eddies but rather for sampling on the synoptic meteorological scale and positive identification of an eddy across the AIDJEX array is difficult.

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The FRAM I Expedition

The Fram I Expedition

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Introduction

Geophysical and oceanographical exploration of the Arctic Ocean has progressed largely with the aid of drifting research stations established on pack ice. The earliest drift expedition was carried out between 1893 and 1896 by the Norwegian scientist and explorer, Fridtjof Nansen, who allowed his especially constructed vessel, *Fram*, to freeze into the ice to be carried by winds and currents. During this time Nansen and his men conducted a remarkable and wide-ranging program of scientific studies.

Over the past three decades, a number of manned scientific research stations have been established by the United States on arctic sea ice in the Amerasia Basin of the Arctic Ocean. These stations were supported by aircraft which were based at the Naval Arctic Research Laboratory in Barrow, Alaska. Increasingly, however, scientific interest has grown in the Eurasia Basin of the Arctic Ocean, which is not readily accessible by air from Alaska. The Eurasia Basin contains the Arctic Midoceanic Ridge, which extends in a straight line for 2000 km between the Greenland-Spitsbergen Passage and the Laptev Shelf. The Eurasia Basin is also the region within which the waters of the Atlantic Ocean mix with those of the Arctic. A number of geophysical, oceanographic, and climatic questions center around these two features of the Eurasia Basin.

To study some of these problems, a plan was devised to freeze an icebreaker into the pack ice to repeat the drift of the *Fram* [*National Academy of Sciences*, 1976]. However, by the summer of 1977, it was apparent that the U.S. Navy plan to freeze the *USCGC Burton Island* into the arctic ice would not receive sufficient U.S. interagency support. Therefore, in August 1977, at the Third Symposium on Antarctic Geology and Geophysics at Madison, Wisconsin, a small group of interested arctic scientists (T. Gjelsvik, F. Roots, L. Johnson, and L. DeGoes) met to discuss the matter. It was the unanimous and enthusiastic conclusion that some action was needed to spur scientific research in the eastern Arctic. The concept of *Fram I* was thus initiated.

EOS, vol. 60, pages 1043-1044
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Planning

The scientific plan was first discussed by U.S., Canadian, and Norwegian scientists at a meeting in Seattle in September 1977. In order to broaden the base of scientific research, all interested scientists were invited to a meeting in Copenhagen on January 31, 1978, which was held under the auspices of the Commission for Scientific Research in Greenland. Here the scientific program, as constrained by the available logistic support, was defined. It was considered important that the scientific program be as broad as possible in this region which is so little explored in nearly all scientific areas. Timing was coordinated to take advantage of the Lomonosov Ridge Experiment (Lorex) of Canada [*Weber*, 1979] so that cooperative programs could be arranged.

Fram I was organized as a U.S. station, with participation by Danish scientists arranged for through the Commission for Scientific Research in Greenland, Norwegian scientists through the Norwegian Polar Research Institute, and U.S. scientists through Lamont-Doherty Geological Observatory under contract to the Office of Naval Research. The Bedford Institute of Oceanography served as the Canadian focal point.

In July 1978, the Polar Science Center of the University of Washington submitted a proposal to the Office of Naval Research to take on major responsibilities in the areas of planning and coordination, as well as management and field services. With the Office of Naval Research approval to proceed, Polar Science Center, in the fall of 1978, started the detailed planning process, which included purchasing of camp equipment and negotiating contracts for aircraft and personnel support services.

Scientifically, the basic plan was to establish *Fram I* on magnetic anomaly 5 and thence drift over the southern axial valley of the active spreading center of the Arctic Midoceanic Ridge, across the Nansen Fracture Zone, and up the continental slope of Greenland. This track would thus satisfy the majority of the stated scientific needs. After a short geophysical program on the shelf, the camp would then be abandoned about mid-May. As it turned out, however, the ice drift did not follow the projected trajectories and had not reached the shelf area at the end of the program.

The problem of logistics, like that faced by Lorex, was complex. It was decided to paradrop the drummed fuel and explosives via a low-altitude deployment (LAD) using Military Airlift Command (MAC) C-130's from Thule.

Execution

On February 12, 1979, all field equipment was shipped from Anchorage to Greenland on a commercial C-130 aircraft with two project personnel. One went to Nord, with the approximately 30,000 lbs. (13,608 kg) of equipment, to start preparations for the project there and one remained at Thule to coordinate efforts there. Nord, a small Danish military base in northeast Greenland, was utilized as the prime logistic support base for *Fram I* through the generosity of the Danish Defense Command.

In late February and early March, project aircraft, equipment, and personnel started arriving at Thule.

On March 11, Fram I was established at approximately 84°24'N. 06°00'W. after the site had been visited twice in the preceding week during reconnaissance by the Twin Otter aircraft.

By March 20, all personnel were at the ice camp, and by March 22, all primary equipment and supplies had been delivered to the station. In 22 Twin Otter flights and 5 Tri-Turbo 3 (TT3) flights, a total of approximately 80,000 lbs (36,288 kg) of cargo and personnel was airlifted from Nord to Fram.

By March 23, the 317th Tactical Airlift Wing of MAC had completed their mission of air-dropping fuel, including 300 drums of JP-4, 72 drums of JP-5, 16 drums of Mogas, and 10 tons of explosives from an altitude of 1600 feet (487.7 m). All pallets landed safely. Only one pallet went through thin ice with the loss of parachute and rigging; however, the drums were recovered by helicopter. All material was rigged in Thule for paradrop by the Army's 18th Airborne Corps.

During the last week in March, as the science program had just started into full operation, the camp was split in two by a crack running through the Bedford Institute hydrohole. With minor relocation away from the crack, the sampling program continued almost uninterrupted from what had now become two camps separated by approximately 1 km. The lead separating the camp eventually refroze and became a Twin Otter runway. With some ongoing ridging and cracking, the ice held together until the end of the program. After an 'abnormal' northerly drift during the month of March, *Fram I* finally started moving south in April.

A gradual reduction of the *Fram I* program began on May 8th, a few days ahead of schedule. The reason for this came from a combination of circumstances; the ice in and around the camp was becoming very active, the approach of summer with foggy weather conditions started to curtail flight operations, and science objectives for the most part were met. Although the camp at the time was moving at a rapid rate it was apparent that it would not reach the planned conclusion of the scheduled drift, the continental margin of Greenland.

The last day of data collection was on May 13, and by May 15 all personnel were off the ice, and the experiment was completed. Poor weather and the loss of the runway on the final day resulted in more equipment being left behind than had been planned. In particular, several shelters with furnishings and kitchen appliances were abandoned. Remaining fuel was only 5%–6% of the initial cache.

On May 16, the helicopter and the Twin Otter left Nord for Thule, and the TT3, after a final buoy mission on May 18, left Nord for Thule on May 19. Two C-130 aircraft (one on May 17 and one on May 22) evacuated equipment and remaining personnel from Nord to the U.S.

The Scientific Program

Navigation

Fram I drifted mainly southward as expected, except for an initial northward movement under southerly winds. The drift track, covering nearly 300 km, is shown in Figure 1. All positions for the camp were determined with the U.S. Navy Transit satellite navigation system using Magnavox 1502 and 706 receiver units. The two portable 1502 units were used for most of the camp positions and were also taken to remote sites on occasion for absolute positioning for geophysical surveys. Between March 18 and May 12 a total of 1178 acceptable fixes were obtained for *Fram I*. Maximum standard deviations based on Doppler data residuals were 64 m in latitude and 88 m in longitude. The Omega navigation sets in both the Twin Otter and the helicopter generally provided reliable navigation for remote surveys.

Bathymetry

Ocean depth along the track of *Fram I* was monitored continuously with a 12-kHz echo sounder. Spot depth soundings away from camp were also obtained during geophysical surveys by using the helicopter. A bathymetric profile along the drift track (Figure 2) showed depth gradually decreasing as the station drifted over the flank of the Arctic Midoceanic Ridge from its initial location above the Pole Abyssal Plain (4000 m). At the time of evacuation, *Fram I* was located in 2300 m of water, 30 km from the ridge axis as determined during helicopter surveys.

Gravity

During the drift, gravity was measured continuously with a Lacoste and Romberg Model G gravimeter especially modified, with variable damping and electronic readout for use on pack ice. This instrument was also used for helicopter surveys. The results will provide supplemental information for geophysical crustal interpretations and will furnish geodetic data in an area where little such information existed previously.

Deep Seismic Refraction

Crustal velocity structure and its anisotropy were measured with 12 seismic refraction profiles which extended to distances of from 40 to 100 km from *Fram I*. Both an ocean bottom seismometer and an array of sonobuoys were used as receivers. The profiles cover the area from the flanking abyssal plain to the axial valley and should provide details of lithosphere structure beneath this slowly spreading ridge.

Sub-bottom Profiling, Shallow Seismic and Microearthquakes

A 40 cubic inch (101.6 cm^3) air gun and a single hydrophone receiver were used to survey sediment thickness. On the Pole Abyssal Plain, sediment cover was represented by over 1 second of two-way travel time. As the station drifted toward the ridge crest, sediment thickness thinned progressively. Seismic profiles at ranges of about 10 km were shot to sonobuoy receivers to determine the structure of the upper sediment layers. The three to six sonobuoy receivers were spaced several kilometers apart. They were operated in a continuous mode in order to monitor microearthquakes in the vicinity of the Midoceanic Ridge. Near the ridge axis, seismic events were recorded at the rate of two per hour.

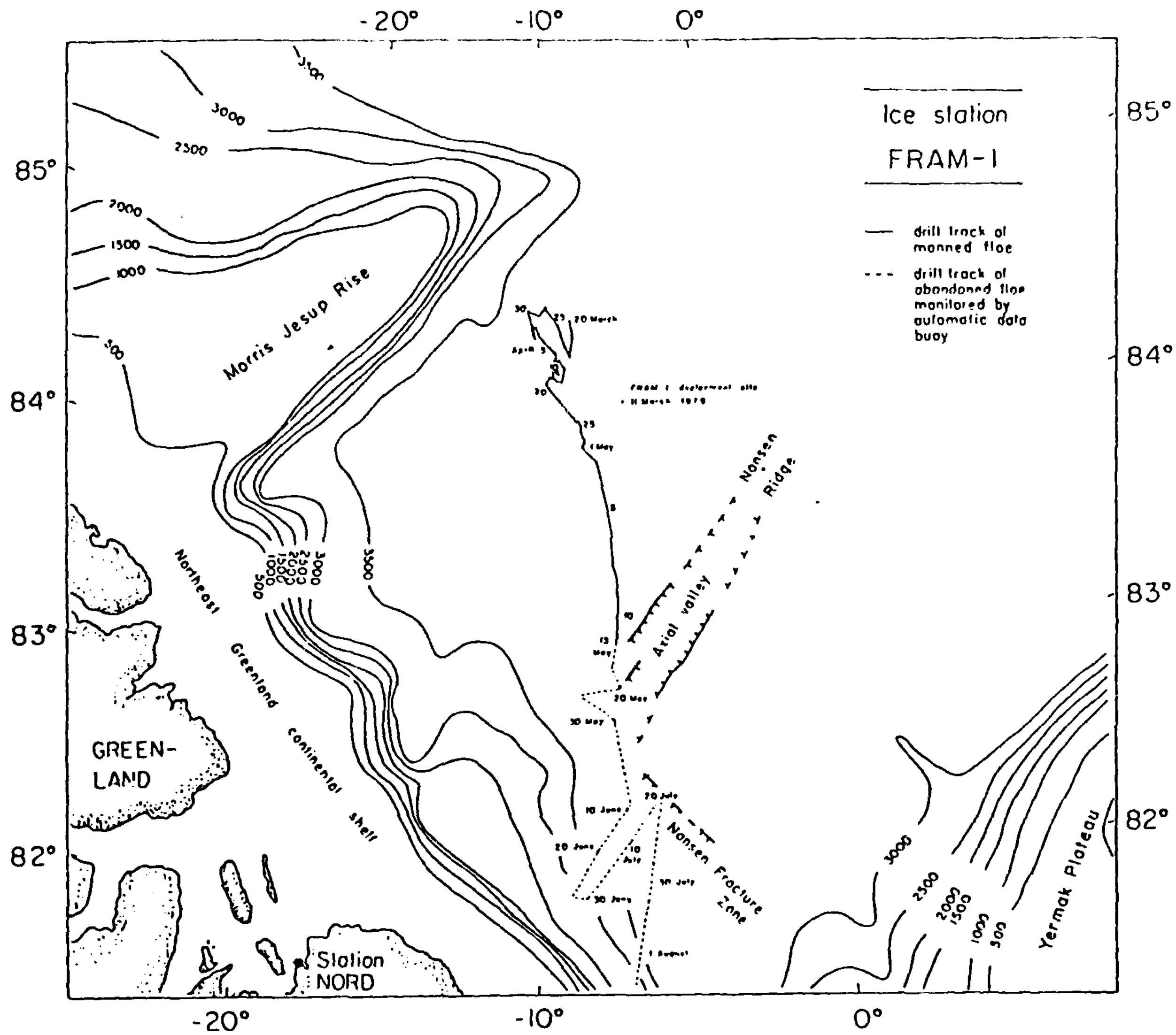

Fig. 1. Drift track of ice station *Fram I* in the Arctic Ocean north of Greenland.

Helicopter Geophysical Surveys

Regional geophysical surveys were conducted with the helicopter based at the camp. Landings were made at 5-km intervals for gravity and depth observations. Four hundred kilometers of such survey line was flown. In addition 200 km of continuous aeromagnetic lines were completed.

Physical Oceanography

The upper ocean was sampled for temperature, salinity, and velocity on various time and space scales. Hydrographic profiles were taken to a depth of 270 m with an ODEC/CSTD instrument, both at *Fram I* and at sites remote from the camp. A total of 105 casts were made with this instrument, 75 of these being taken at remote sites up to 150 km away from the camp. At the camp, profiles were taken twice each day to a depth of 750 m with a Plessey 9040 CTD instrument and to 200 m with a profiling current meter. There was considerable variability in the salinity structure of the upper layers. An extensive surface front was identified with a salinity difference of 0.7 ppt within a distance of 10 to 15 km. The front was accompanied by a distinct current system.

Both sea ice and water were sampled for later analysis of their tritium content.

Underwater Acoustics

Explosive sources were detonated at both *Fram I* and the Lorex satellite camp, Iceman, for long-range sound propagation experiments between the two stations. The effect of water and ice properties on low-frequency propagation across the Eurasia Basin was studied. Ambient acoustic noise was also investigated at each station. Basin reverberation was also determined by using the large explosions, as well as the other smaller shots, set off for seismic refraction use.

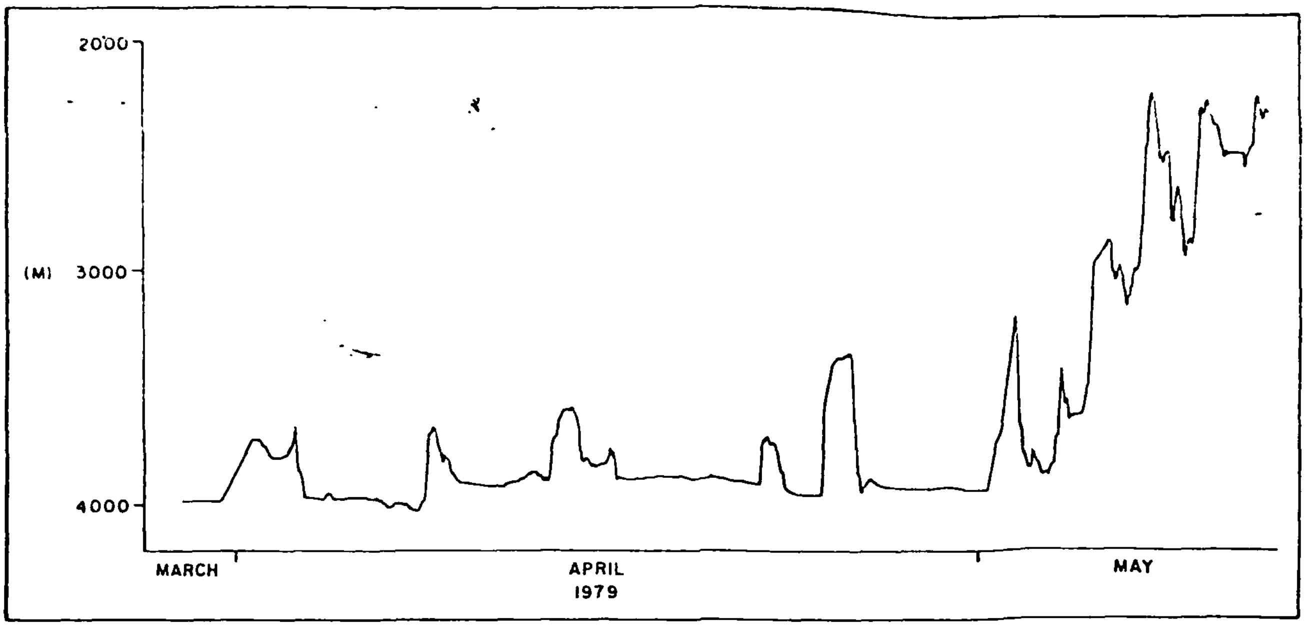

Fig. 2. Bathymetric profile along the *Fram I* track.

Marine Biology

Primary productivity, nutrients, chlorophyll, salinity, and temperature were sampled extensively in the upper 200 m of the ocean. The productivity of flora on the bottom of the pack ice was also studied. Mesoplankton were sampled throughout the water column in order to study their relation to hydrographic parameters.

Polar Bear Studies

Polar bears, which are now a protected species, have been of great importance to native hunters in the past. The migration pattern of these bears is still largely unknown and a matter of controversy. To provide information on their migrations, collars instrumented for satellite telemetry were successfully placed on four polar bears to allow them to be tracked over large distances. Preliminary results show some bears covering a distance of 250 km in 1 week. Also, seven bears were tagged for later identification as a further aid to establishing migration patterns.

Meteorology and Electromagnetics

The atmospheric boundary layer above the ice flow was studied with a sensor array on a 10-m tower. Weather data were transmitted twice daily for inclusion in the World Meteorological Organization surface charts. Pollution of the polar air was investigated with sampling of mercury, sulfur, and aerosol content.

Three meteorological data buoys were deployed in the area north of Svalbard as part of the Garp project, including one which was activated on the abandoned Fram I campsite. This buoy has provided further drift data on the station which exited into the Greenland Sea during August.

The reception of ELF/VLF radio signals was monitored and HF absorption was measured.

The following individuals were responsible for scientific programs and support activities:

Navigation, bathymetry, gravity, and physical oceanography: Kenneth Hunkins, Lamont-Doherty Geological Observatory of Columbia University;

Shallow seismic, microearthquakes, helicopter geophysical surveys, air pollution, and electromagnetics: Yngve Kristoffersen, Norsk Polarinstitutt, Oslo;

Deep seismic refraction and sub-bottom profiling: Robin K. H. Falconer, Atlantic Geoscience Centre, Bedford Institute of Oceanography, Department of Energy, Mines, and Resources, Dartmouth, Nova Scotia;

Marine biology: Jean Just, Zoologisk Museum, Copenhagen;

Polar bear studies: Christian Vibe, Zoologisk Museum, Copenhagen;

Underwater acoustics: Henry Kutschale, Lamont-Doherty Geological Observatory of Columbia University;

The chief scientists were Kenneth Hunkins and Yngve Kristoffersen.

The operations manager was Andy Heiberg, Polar Science Center, University of Washington. Camp managers were Al Heilscher, Polar Science Center, and J. Ardai, Lamont-Doherty Geological Observatory of Columbia University.

Acknowledgments

This work was supported by the Office of Naval Research under contract N00014-76-C-0004. This is Lamont Doherty Geological Observatory Contribution 2931.

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The FRAM III Expedition

The *Fram 3* Expedition

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Introduction

On the fourteenth of March 1981, *Fram 3*, the third in a series of four U.S. manned ice camps, was established in the eastern Arctic Ocean at 84.32°N, 20.07°E for oceanographic and geophysical research in the Eurasian Basin north of the Greenland-Spitzbergen Passage.

Investigators from several institutions in the United States, as well as from Canada and England, participated in studies of physical and chemical oceanography, low-frequency underwater acoustics, geophysics, and the mechanics and propagation of waves through sea ice. A Bell 204 helicopter and crew were stationed at *Fram 3* throughout the drift in order to support research efforts and camp operations. Several oceanographic buoys that used satellite telemetry were deployed during this time period.

Oceanographically, the *Fram 3* region is of interest because of the proximity of the polar front, which separates the outflowing Arctic surface water from the inflowing Atlantic water in the Greenland-Spitzbergen Passage and northward. Significant amounts of heat and salt are transferred through this strait as compared to other passages into the Arctic Ocean, such as the Bering Strait and the Arctic Archipelago [*Aagaard and Greisman*, 1975]. Variations in these transports of heat and salt through the Fram Strait may prove to be a significant factor in climate change. Estimates of vertical fluxes in heat and salt were also part of the ongoing experiments of the *Fram* expeditions. These would help determine spatial variations of heat loss from the Atlantic water into the upper layers of the Arctic Ocean (less than 200 m). It was also hoped that data might also provide more insight into the origin and effects of the steep pycnocline that lies directly beneath the mixed layer (50 m) and the upper extent of the Atlantic water (200–500 m). Current theory suggests that this layer is the product of wintertime ice formation on the shelves surrounding the Arctic Ocean. The resultant cold, saline shelf water is later advected into the Arctic Ocean on surfaces of constant density that reside in the depth range of 50 to 200 m. Due to the very large gradients of temperature and salinity in this depth range, the vertical transfer of heat from the Atlantic water to the upper layers of the Arctic Ocean is effectively minimized. Mesoscale CTD (conductivity, temperature, and depth) surveys were also conducted by helicopter to depths of 500 m in order to expand the areas of observation as well as to map various features and their temporal variations on length scales of 10 to 300 km. A profiling current meter-CTD unit was also used at the main camp to study the response of the upper ocean to storms.

At camp, samples for chemical and biochemical analysis, ranging in volume from 1.2 to 100 l, were taken at many levels throughout the water column. Various projects were designed to study the concentrations of tritium, oxygen, alkalinity, nutrients, respiratory enzymes, trace metals, ammonia, dissolved silicon, and bomb-produced C-14.

Further geophysical information was also to be gathered in the areas of the Nansen Basin and Yermak Plateau. The Nansen Basin is of interest because of its thin oceanic crust which is a result of the very slow spreading of the Arctic Mid-Ocean Ridge, located several hundred kilometers to the west. The Yermak Plateau may be continental in origin, however, it does not fit well into a reconstruction of the local continental land masses. In order to study these features, observations of heat flow, gravity, short sediment cores, seismic reflection profiles, and continuous precision depth recordings were made at *Fram 3*. Several seismic refraction lines were also conducted in the vicinity of the Yermak Plateau and within the Nansen Basin with the aid of the helicopter.

With all scientific goals accomplished, *Fram 3* was evacuated on May 13, 1981, at a position of 81°43'N and 3°15'E. The resulting net drift of 361 km proved to be much longer than that of *Fram 1* (163 km) and *Fram 2* (83 km) stations during the previous years. This not only allowed experiments to be carried out over a large geographical area but also over a range of ocean depths, from a maximum of 4088 m in the Nansen Basin to a minimum of 727 m above the Yermak Plateau. Figure 1 shows the drift tracks of the three *Fram* stations superimposed on the general bathymetry of the Arctic Ocean.

Background

After completion of the Arctic Ice Dynamics Joint Experiment (AIDJEX) in the Beau-

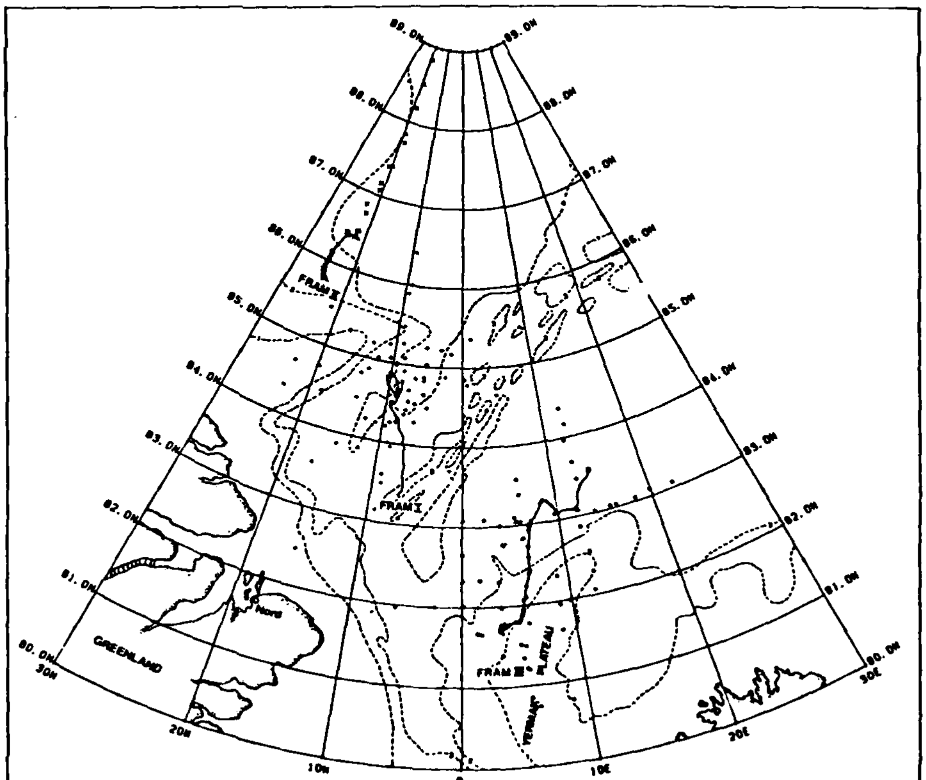

Fig. 1. Locations of all portable CTD stations taken during the *Fram 1, 2,* and *3* experiments. Drift tracks of the individual camps are also shown in reference to Greenland, Spitzbergen, and bottom topographic contours. The end of the drift track is labeled by the camp identification. Depths are given in kilometers.

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[6]Scott Polar Research Institute, Cambridge, England.
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0096–3941/82/6335–0627$01.00

fort Sea in 1976, where ice mechanics in the central pack was emphasized, the United States made a concerted effort to begin geophysical and oceanographic investigations in the eastern Arctic Ocean. The *Fram* expedition series of short-duration manned camps located on the drifting pack ice north of Greenland has been the focus of this effort. Cooperation and participation from Norway, Denmark, and Canada in several of the expeditions have been an important aspect in these projects.

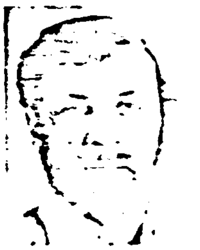
The project name *Fram* echoes that of the specially designed ship that was frozen into the pack ice of the Arctic Ocean near the New Siberian Islands by the Norwegian explorer Fridtjof Nansen, in a milestone of polar scientific exploration. During the drift of the original *Fram* (1893–96), an unprecedented amount of information was collected over the deep ocean of the Eurasian Basin.

The first of the modern *Fram* camps was established on the drifting ice at a position of 84°24'N, 6°00'W, on March 11, 1979 (Figure 1). *Fram 1* was a U.S. drifting ice station that had scientific and logistic participation by Norway, Denmark, and Canada. Away from the main camp a CTD survey, seismic refraction lines, microearthquake investigation, and polar bear migration studies were supported by helicopter. At the main camp there were programs in physical, chemical, and biological oceanography, as well as surface weather monitoring. Although the drift of the camp did not reach its anticipated destination by evacuation time, a large amount of geophysical and oceanographic data were obtained [*Kristoffersen*, 1979; *Hunkins et al.*, 1979*a*, *b*].

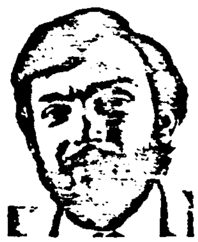
Preliminary scientific results from *Fram 1* were presented at the special session 'Arctic Geophysics and Oceanography: LOREX and *Fram 1*' during the American Geophysical Union Spring Meeting 1980. Interesting results suggest that the crust in the Amundsen Basin is less than 3 km thick and is related to the slow spreading rate of the Arctic Mid-Ocean Ridge. *Reed and Jackson* [1981] have also formulated a theoretical model for the relationship between crustal thickness and spreading rate for the ridge. Data not only from the *Fram* expedition but also from numerous areas around the world agree with the model. Also observed on one of the refraction lines was a local hot spot over which the crust was significantly thicker, 8 km [*Jackson et al.*, 1982].

Although baroclinic eddies of the type highly prevalent in the Beaufort Sea north of Alaska [*Manley*, 1981; *Dixit*, 1978; *Hunkins*, 1974; *Newton et al.*, 1974] were not observed, a prominent front was found in the mixed layer. Heat flux from the Atlantic water into the surface mixed layer is effectively minimized by the steep pycnocline overlaying the Atlantic water, even close to the main polar front region [*Aagaard et al.*, 1979; *McPhee*, 1980*a*]. Both portable and camp-based CTD measurements documented a type of frontal intrusion of colder, more saline water from the south and may have originated from the arctic continental shelves [*Aagaard et al.*, 1979; *Hunkins and Manley*, 1980; *McPhee*, 1980*b*].

In the following spring, *Fram 2* was established on March 14 for the study of long-range, low-frequency, underwater acoustics, and later its two manned satellites, camp 1 and camp 2, were also set up [*Allen et al.*, 1980]. Marine geophysics and physical oceanography were conducted at the main camp as well as along lines radiating away from the



James Morison *is a physical oceanographer at the Polar Science Center, University of Washington, Seattle. He holds a B.S. and an M.S. (mechanical engineering) from the University of California at Davis and received a Ph.D. in geophysics from the University of Washington in 1980. He is a member of Sigma Xi, the American Geophysical Union, and the Current Meter Technology Committee of the IEEE Council on Oceanic Engineering. His current research interests are in experimental and theoretical studies of the dynamics and thermodynamics of the upper Arctic Ocean and marginal ice zones.*



Peter Wadhams *is assistant director of research at the Scott Polar Research Institute, University of Cambridge, England, and leader of the Sea Ice Group there. His research interests include the topography and thickness distribution of sea ice in the Arctic Ocean, the interaction of ocean waves with sea ice, and the dynamics of ice edge processes such as band and eddy formation. From 1980–81 he was visiting professor at the Naval Postgraduate School, Monterey, and he is involved with the planning of the MIZEX ice edge experiment.*

Stuart Moore *is a research technician at the Scott Polar Research Institute, working primarily for the Sea Ice Group. He is involved mainly in the design and development of field and laboratory equipment and has participated in numerous Arctic and Antarctic field experiments.*

Valery Lee, *B.S. (earth and planetary sciences) M.I.T., M.S. (physical oceanography) University of Miami; a newcomer to arctic research and ice camps, she says she's already hooked. Valery is working with the Tritium Lab in Miami, where they do proportional gas counting to measure tritium and radiocarbon levels in the ocean. She likes to get out in the field and do some hands-on oceanography so as not to lose touch with 'what it's all about.' Sailing her 15' knockabout in Biscayne Bay provides an excellent antidote for those ice-camp blues.*

Lou Codispoti *is a principal investigator at the Bigelow Laboratory for Ocean Sciences. He received his B.S. in chemistry from Fordham University and his M.S. and Ph.D. in oceanography from the University of Washington. He is a member of the American Geophysical Union, the American Society of Limnology and Oceanography, and the Arctic Institute of North America. His research interests include nutrient and carbon dioxide chemistry in highly productive regions, the nitrogen cycle in oxygen deficient waters, and the chemical oceanography of the Arctic Ocean.*

H. Ruth Jackson *received a B.Sc. from Dalhousie University and an M.Sc. in geophysics from Durham University in 1978. She is employed by the Atlantic Geoscience Centre of Bedford Institute of Oceanography. She participated in the Fram 1, 2 and 3 expeditions and is involved in continuing research in the arctic.*

Ted Packard *is a principal investigator at the Bigelow Laboratory for Ocean Sciences. He received his B.S. in life sciences from M.I.T. and his M.S. and Ph.D. in oceanography from the University of Washington. His research is focused on biologically regulated chemical reactions in the ocean. He is a member of the American Chemical Society, the American Geophysical Union, the American Society of Limnology and Oceanography, and the Catalan Biological Society.*

Kenneth Hunkins *is a senior research associate at Lamont-Doherty Geological Observatory and an adjunct professor in the Department of Geological Sciences at Columbia University. His polar research centers on currents of the Arctic Ocean and their driving forces of wind and gravity, and it includes spatial scales ranging from the large-scale mean circulation through mesoscale eddies to small-scale processes and internal waves. He is also studying current behavior in submarine canyons of the East Coast with an array of moored oceanographic sensors. He lives in Nyack, New York.*

Thomas Manley *received a B.S. in mathematics and geology at Kent State University in 1974. Further graduate degrees (M.A., 1976; M.Phil., 1978; and Ph.D., 1981) were earned through Lamont-Doherty Geological Observatory of Columbia University in the field of physical oceanography. His dissertation dealt with mesoscale eddies of the Arctic Ocean and their characteristics and effects on energy, heat, and salt balances. Research interests include all facets of physical oceanography in the Arctic Ocean.*

Peter Jones *obtained his education at the University of British Columbia, receiving a Ph.D. in 1963. Since 1973 he has been at the Bedford Institute of Oceanography, where much of his work has focused on the chemical oceanography of arctic regions.*

station, using a Bell 204 helicopter as in the *Fram 1* experiment. Scientific objectives and preliminary results of the underwater acoustic program are given by *Dyer and Baggeroer* [1980] and *Baggeroer and Dyer* [1982]. Some of the more notable results were the highly variable ambient noise conditions and good signal-to-noise ratios from backscattering of signals by features as far away as the Chukchi Sea. Seismic refraction work at *Fram 2* indicates that 2 to 3 km of sediment overlay a crust of less than 5 km, agreeing fairly closely with the *Fram 1* results [*Duckworth et al.*, 1982].

A subsurface mesoscale eddy was observed on a helicopter traverse to camp 1 from *Fram 2*. This is only the second observation of a subsurface mesoscale eddy in the Eurasian Basin. The first observation of such a feature was made by Shirshov in 1937 from the Soviet drifting ice station *NP-1* [as reported by *Belyakov*, 1972]. Thickness of the eddy was about 175 m and was in the depth range of 50 to 225 m. The depth of maximum angular velocity was calculated to be at 90 m. These characteristics are similar to those observed in the Beaufort Sea during the main AIDJEX experiment.

Staging of *Fram 3*

In late February of 1981 the advance team for *Fram 3* accompanied a group of U.S. Army parachute riggers from the 612th QM Company of Fort Bragg, North Carolina, as well as the support crew and officers of three U.S. Air Force C-130 Hercules transports from the 317th Tactical Air Wing of Pope Air Force Base, North Carolina, to Thule, Greenland. These C-130's were then used to transport all scientific and logistic gear to the Danish base at Nord on the northeast corner of Greenland, while the Army riggers at Thule prepared the necessary lumber, fuel, and explosives for eventual C-130 paradrops over *Fram 3*.

A DeHavilland Twin Otter and a specially modified DC-3 'Tri-Turbo' were then used for location, establishment, and support of the drifting ice camp. On March 13, *Fram 3* was established on a large multiyear floe that measured 3 km by 5 km and had an average thickness of 4 m. Bad weather and radio communications prevented further flights to *Fram 3* until 5 days later.

By mid-April, 203,000 pounds of fuel, lumber, and explosives were paradropped to *Fram 3* by the C-130's. An additional 75,000 pounds of scientific and logistic gear were landed at *Fram 3* by way of 24 Twin Otter and five 'Tri-Turbo' flights. From April 6 to May 5 (last day of the scientific program) an average of 19 people were stationed at the camp. By the end of the manned drift, a total of 895 'man days' had been logged at the camp.

Final evacuation from *Fram 3* was on May 13, at a position of 81°43'N, 3°15'E, 61 days after the first landing. The net drift of the ice station was 361 km to the southwest at an average drift rate of 5.9 km/d. Due to the meandering of the camp along the drift track, the total distance covered was 505 km, with a computed average drift velocity of 8.3 km/d.

Following a few days of packing at Nord, two C-130s from the 36th TAS of McChord Air Force Base, Washington, removed all remaining gear and personnel from Nord to Thule Air Force Base and then back to the United States.

Fram 3 Scientific Programs and Preliminary Results

The institutions involved in scientific programs on *Fram 3* and available preliminary results are listed below.

Lamont-Doherty Geological Observatory

Station physical oceanography. Profiles of conductivity, temperature, and oxygen were made to depths of 1000 m at least three times each day, using a Neil Brown CTD equipped with an oxygen sensor. Stations to the bottom of the ocean were taken on a weekly basis. A pinger mounted on the CTD permitted data to be taken within a few meters of the bottom. A 12-bottle rosette sampler and reversing thermometers were used to obtain temperature, salinity, and pressure data for later calibration.

Additional CTD stations were taken to provide geochemists with small 1.2-l samples of water for the study of tritium, oxygen, dissolved nutrients, and gases within the water column; to provide intercalibration stations between the portable ODE (ocean data equipment) and Neil Brown CTD's; and to provide a concurrent station at *Fram 3* at those times that the portable CTD was away from camp on a helicopter transect.

Preliminary results show passage of the main camp through the polar front, a somewhat linear surface feature on the order of 100 km wide and extending to a depth of roughly 300 m. Large temperature and salinity variations were observed frequently within this depth range. Fine structure was also highly variable in this area. Yo-yo CTD stations that were taken every 20 min to depths of 400 m were, in several cases, inadequate for keeping track of the individual fine-structured features. Well-mixed boundary layers were also observed at abyssal depths as well as along the slope and top of the Yermak Plateau.

Mesoscale helicopter oceanographic survey. Helicopter mobility provided the means to study mesoscale features and their spatial variability in the upper 500 m. This was accomplished by using a portable CTD, as in the *Fram 1* and *Fram 2* expeditions. Figure 1 shows the positions of the CTD stations taken in the vicinity of each of the *Fram* ice camps. A major objective of this program was to map the polar front in the vicinity of the *Fram 3* drift track. Another objective was to study any eddies within the region. It is hoped that further knowledge about these features will aid in the understanding of lateral mixing within the Arctic Ocean and of transport processes across the polar front. The camp passed over two features, 15 and 25 km across, of anomalously high salinity and temperature, which had apparently originated from Atlantic water. They appear to be eddies shed by the polar front. Work done by *Hunkins* [1981] indicates that this region is baroclinically unstable and that features with a scale of approximately 30 km are the fastest growing (doubling time of 2 weeks).

Alignment of the polar front was generally NE-SW. Its location, on the basis of salinity, was fairly stationary over the 1-month observation period, although temperatures showed a more variable pattern.

Ocean currents. The properties of inertial and internal waves were investigated with an array of five Aanderaa current meters equipped with conductivity, temperature, and pressure sensors. Two strings of current meters were deployed—one in a lead at the edge of the large *Fram* ice floe, 5 km from the camp; and one at camp itself. The 'lead string' had instruments suspended at depths of 25 and 100 m, while the 'camp string' had instruments at 25, 100, and 480 m.

The 100-m lead instrument documented the passage of the camp through part of the frontal zone. Superimposed upon the frontal transition of temperature and salinity along the steady southwest movement of the camp are the signatures of the anomalous intrusion of warmer, more saline water (Figure 2), previously described in the mesoscale helicopter oceanographic survey. Data from two Aanderaa current meters (25-m lead, 480-m camp) were discarded because of flooding and circuitry problems.

Hydroacoustic observations. Studies of underwater sound propagation were conducted by using sensitive hydrophones and a single

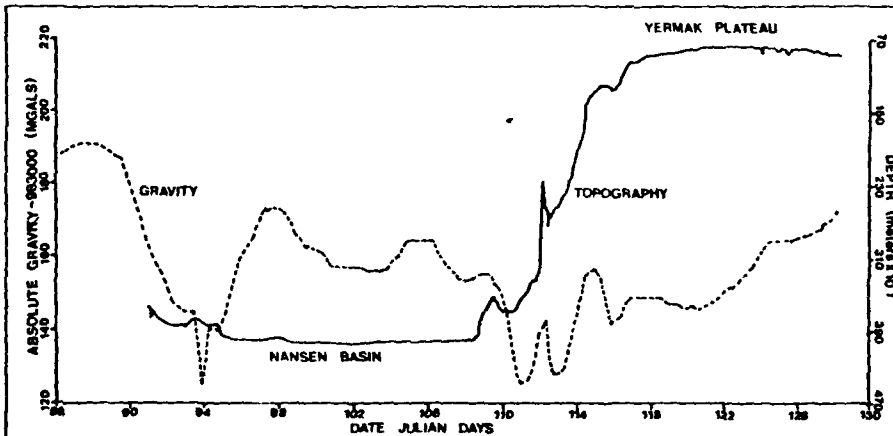


Fig. 2. Temperature and salinity time series recorded at the edge of the large *Fram 3* ice floe. Data were taken by an Aanderra current meter suspended at a depth of 100 m.

geophone. Hydrophones were placed at 1 km and 3 km away from the camp and at depths of 40 m and 60 m, respectively. The geophone was placed on the surface of the ice at a distance of 1.5 km away from the camp. Data were continuously recorded on Hewlett-Packard FM recorders.

Single earthquakes, as well as earthquake swarms, were recorded frequently, with one earthquake recorded every day on the average. Although epicenters of the earthquakes could not be fixed because of the single recording site, most of them apparently originated from the Arctic Mid-Ocean Ridge.

Geophysical observations. A marine geophysical program provided background data on position, depth, magnetic declination, floe azimuth, and gravity. A geophysical data report summarizes these results [*Hunkins et al.*, 1981]. Figure 3 shows the depth and gravity field along the drift track of *Fram 3*.

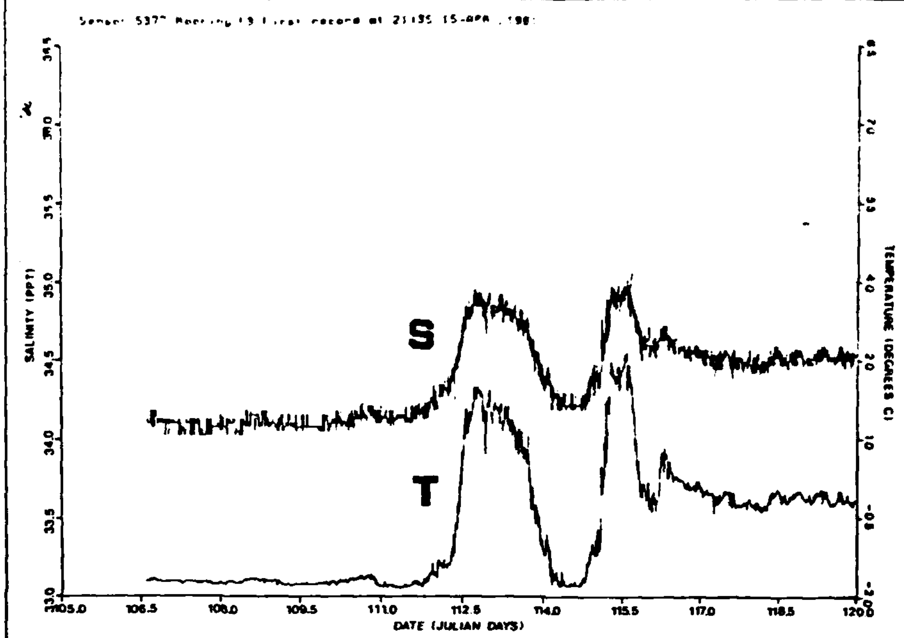


Fig. 3. Gravity and topography along the drift track of *Fram 3*.

Bedford Institute of Oceanography

Chemical oceanography. The Bedford Institute of Oceanography's primary program for chemical oceanography included measurements of oxygen, salinity, alkalinity, nutrients (nitrate, phosphate, silicate), trace metals (Mn, Fe, Ni, Cu, Zn, Cd), and radionuclides (Cs-137, Sr-90). The goal in measuring the first group of components, oxygen, salinity, alkalinity, and nutrients, was to characterize the water in the Eurasian Basin and above the Yermak Plateau and to study chemical processes, e.g., nutrient regeneration, that occur in the Arctic Ocean. More than 100 samples were collected at fairly closely spaced depth intervals from 3800 m to the surface, as the ice camp drifted toward and over the Yermak Plateau. For radionuclides and trace metals the goal was to characterize the water column and to see if there were any near-surface higher concentrations associated with Bering Sea water, as has been observed near the North Pole on the 1979 LOREX expedition [*Weber*, 1979]. Because sample collection was more difficult, especially for the radionuclides that required 100 l of water, fewer samples were collected. About 20 samples for trace metals and 15 for radionuclides were collected between depths of 2500 m and the surface.

A secondary program was to collect ice samples for analysis of alkalinity and some major ions (Ca, Mg, Cl, and SO_4). The goal of this program was to analyze the ice to detect chemical differentiation of ions, which occurs during freezing, and hence possibly to be able to predict ice meltwater content in near-surface seawater from an analysis of major ion content. Altogether, about 15 different ice samples were collected from leads, pressure ridges, and one ice core.

Analyses of the samples are presently underway, and most should be complete within about 3 months. Detailed interpretation of the results will take longer and will be done in conjunction with the physical oceanographic measurements.

Seismics and heat flow. The Atlantic Geoscience Centre of Bedford Institute of Oceanography ran a geophysical and geologic sampling program on *Fram 3* that consisted of seismic refraction, seismic reflection, heat flow, and coring.

The seismic refraction program involved the use of a tethered ocean bottom seismometer. The sound source was from 20- to 100-kg TNT charges carried away from the receiver by helicopter and detonated in areas where thin ice made access to the water possible. A 150-km line along anomaly 7 (26 m.y.) in the Nansen Basin was completed in an area where oceanic crust formed by slow spreading could be investigated. Three lines were run on the Yermak Plateau. Line 2 was run in water depths of about 2000 m on the slope of the Yermak Plateau. Line 3 was parallel to line 2 but on the top of the plateau, and line 4, also on the plateau, was run perpendicular to line 3.

The reflection profiling system was in operation at *Fram 3* from April 11 to May 5, 1981. The ocean bottom seismometer (OBS) was deployed at camp, but the refraction profiles generally ran parallel to structure and were shot away from the seismic reflection line at large angles. The reflection records provided information on the thickness of sediment below the OBS and a cross section across a portion of the Nansen Basin and the Yermak Plateau. The 9000-J Edgerton sparker provided a clear record of sedimentary layers with varying dips on the plateau, but only a minimum thickness of sediment in the basin because oceanic basement is not obviously recorded.

Along the reflection profile, 10 heat flow measurements were recorded with a 2.5-m Applied Microsystems probe, and 10 accompanying short gravity cores of about 30 cm were taken. The heat flow measurement and cores were done at water depths from 3675 to 795 m, accomplishing a line from the edge of the Nansen Basin to the top of the Yermak Plateau.

Refraction lines in the vicinity of the Yermak Plateau indicate that its northern tip is predominantly of oceanic origin, whereas the broader, more southern segment is of continental origin.

Bigelow Laboratory

Chemical and biochemical oceanography. During the first half of the *Fram 3* experiment, observations of the chemical and biochemical properties of the water column were made. These included on-site analyses for dissolved oxygen, ammonia, dissolved silicon, nitrate, nitrite, and reactive phosphorus from samples collected directly beneath the ice cover to a depth of 4000 m. On-site determinations of the activity of the respiratory electron transport system (ETS) were also made on eight samples taken from depths as great as 2000 m. Preserved samples were returned to the Bigelow Laboratory for examinations with a scanning electron microscope and for determination of their nutrient, chlorophyll, phaeophytin, particulate nitrogen, and particulate carbon contents.

With the exception of the scanning electron microscope examinations, all of the laboratory work has been completed. Initial analysis indicates that metabolic rates in the *Fram 3* water column are extremely low. Nitrite and ammonia concentrations were zero or very close to zero throughout the water column, and ETS activities were low in the upper 125 m and undetectable below that depth. This was the first time that ETS activity could not be detected in the deep-sea samples. While these results were not surprising, they will prove useful (when combined with data from other regions) in clarifying the relative importance of the processes that feed the 'deep metabolism' and in constructing an inorganic nitrogen budget for the Arctic Ocean. Although some weak maxima and minima were observed in the vertical dissolved silicon, reactive phosphorus, and nitrate distributions, there was no evidence for the presence of substantial amounts of the high nutrient waters that enter the Arctic via the Bering Strait. In addition, these data do not suggest a large contribution to the subsurface layers from waters formed over the continental shelf during the ice formation season.

Tritium Laboratory, Rosenstiel School of Marine and Atmospheric Science

Chemical Oceanography. Detailed profiles of water samples were collected at three points along the drift track for later analysis of their tritium and ^{3}He content. Results from the earliest samples show highly tritiated water above the halocline, indicating that, at this early stage in the drift, *Fram 3* was situated in a region of outflow from the Arctic Basin. The tritium-salinity relationship of these samples seems to uphold the view that, below the upper mixed layer, Nansen Basin water is composed of binary mixtures of Atlantic source water and predominantly meteoric freshwater [*Ostlund*, 1982]. The derived tritium values of the freshwater source imply an approximate 10-year residence time for the freshwater component in the East Arctic Basin. *Fram 3* tritium-^{3}He ages, which provide an essentially independent estimate of residence time, corroborate this result.

A profile of large-volume water samples was obtained by using a 100-l General Oceanics Go-Flo Sampler. Carbon dioxide gas was extracted from these samples at camp for later radiocarbon analysis. Samples down to 1250 m show a definite presence of bomb-produced ^{14}C; deeper layers show what is most likely some bomb contribution. There is measurable tritium all the way down to 3500 m, indicating that there have been contributions at these depths of water that have been at the surface within the last 20 years.

Polar Science Center—University of Washington

Current velocity-CTD profiling, oceanographic buoys, meteorology. The scientific group from the Polar Science Center carried out three main experiments at *Fram 3*. First, a new Arctic Profiling System (APS) was used during the experiment to examine the response of the upper ocean to storms. An additional goal was to use this device to study the vertical and horizontal circulation patterns within leads. The new APS was built by the Applied Physics Laboratory of the University of Washington and is a more compact version of an earlier instrument described in *Morison* [1980]. The device is a wire-lowered instrument that measures continuous profiles of conductivity, temperature, and velocity. During the experiment, there were three storms for which good records were obtained. During these storms, casts were made to 300 m every half hour. One such sequence of profiles measures the development of a 35-m-thick mixed layer from an initially stratified condition and should provide an especially good basis for comparison with mixed layer theories. Conditions at *Fram 3* were highly variable, and dramatic changes in the water structure, especially temperature, were quite common. The variations are related to the location of *Fram 3* near the ice edge, and the data will be compared to those obtained during a previous cruise (NORSEX 79) in the same region made during the fall of 1979. Unfortunately, no leads opened near camp, and the goal of studying lead circulation was not achieved.

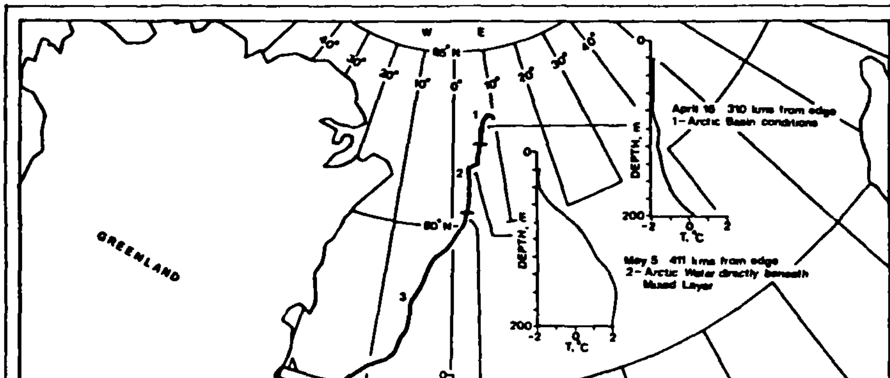


Fig. 4. The drift of the thermistor chain buoy. The device measures temperature to 200 m and transmits through the ARGOS system. During segments (2) and (3) of the drift, the buoy was over warm Atlantic water. During segments (1) and (4) it was over cold polar water.

The second experiment involved the deployment and testing of two new oceanographic buoys built by the Polar Research Laboratory. The buoys are being developed to provide a means of gathering long-term hydrographic data in the upper Arctic Ocean. One buoy is a thermistor buoy (T-buoy) and the other is a temperature-conductivity buoy (T-C buoy).

The T-buoy incorporates an electronics/ARGOS transmitter package in an aluminum tube and a Kevlar cable with thermistors imbedded in it every 20 m, hanging to a depth of 200 m. The buoy transmits temperature from all the sensors through the ARGOS satellite system four times per day.

The buoy was installed at *Fram 3* and left there after evacuation. The primary objectives were to perform intercalibrations with the APS and T-C buoy, provide a picture of the thermal structure in the East Greenland Drift, and test the survivability of the design. Data gathered simultaneously with the APS and the T-buoy generally agree.

After the end of the experiment, the T-buoy drifted south along the coast of Greenland and through Denmark Strait. Figure 4 shows the drift track of the buoy. It is noteworthy that the T-buoy remained in a fixed relation with the three other buoys left at *Fram 3* (two from the Polar Research Laboratory and one from the Norsk Polarinstituit) until just north of Denmark Strait, indicating the *Fram 3* ice floe maintained its integrity for a remarkably long time. The T-buoy ceased functioning on August 22, near the ice edge at 67°35′N 25°41′W.

The temperature profiles in Figure 4 show characteristic thermal regimes in the drift. The first shows a deep thermocline, indicating the buoy was on the cold side of the polar front. The second and third regimes show a shallow thermocline, indicating the buoy was on the warm side of the front, in spite of being 50–100 km from the ice edge. In the fourth regime the thermocline is again quite deep, but surface heating appears to be important. Fluctuations in the temperature records on the time scale of a couple of days suggest the presence of meanders or eddies near the front. The continued survival of the instrument, even in the rigorous ice edge region, bodes well for the survivability of such buoys in the pack ice.

The T-C buoy was developed as a step toward remotely measuring both temperature and conductivity for the study of the mixed layer in the Arctic. It incorporated three temperature and conductivity sensor pairs at 15 m, 30 m, and 50 m, suspended below a surface electronics package. In this buoy, temperature and conductivity are averaged over 3-hour periods. The average values are then transmitted during a once daily, 5-hour transmission window.

The buoy was operated at *Fram 3* for the purposes of testing and intercalibration with other systems, only while personnel were at the camp. The results indicate it worked well. Instantaneous conductivity values from APS and the T-C buoy generally agree within ±0.001 s/m, and the temperature values agree within less than ±0.02° C. It has been found that the deepening of the mixed layer examined with the APS could also be observed with the T-C buoy. This illustrates the usefulness of the T-C buoy, even in studies of relatively short-term processes.

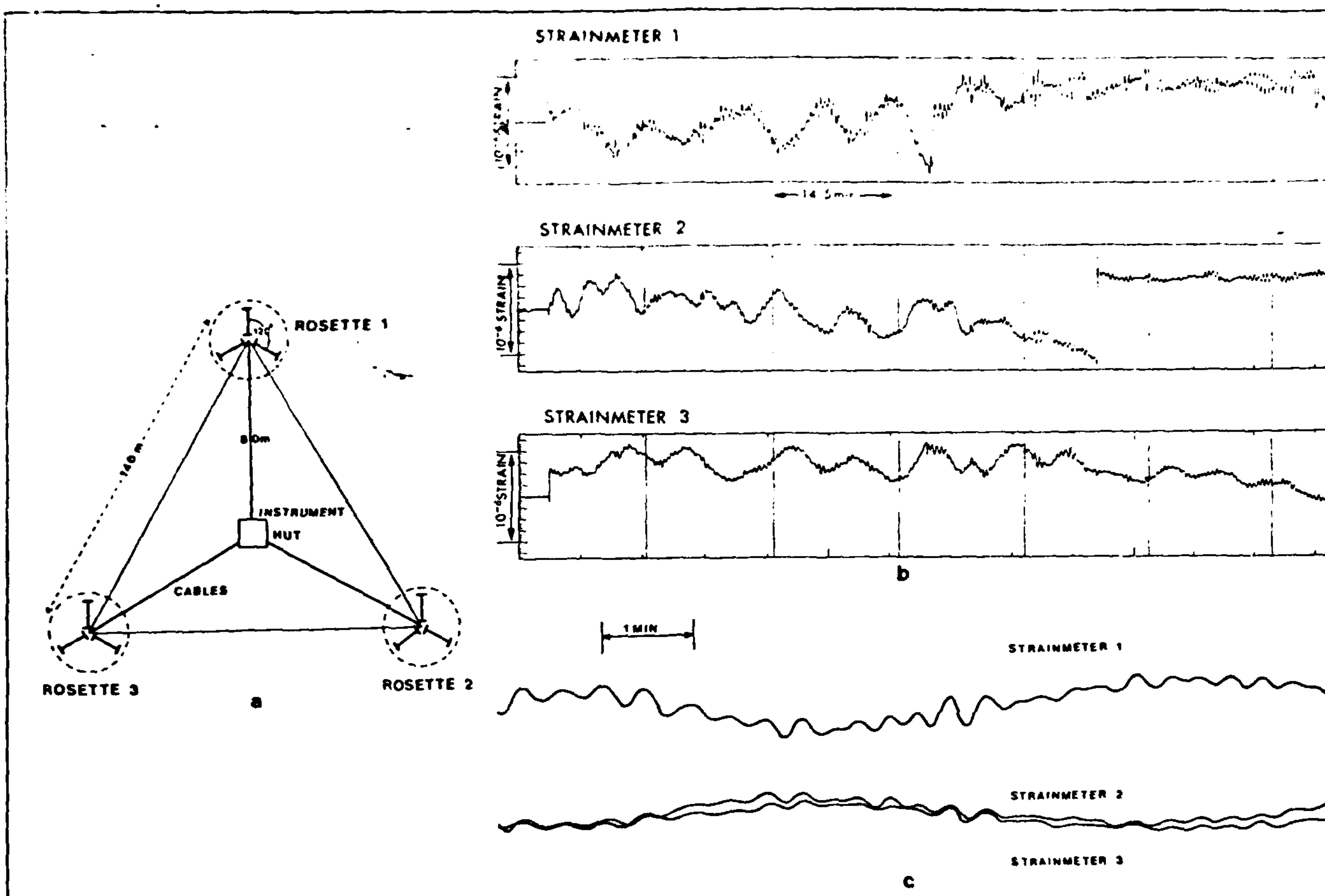


Fig. 5 (*a*) Configuration of the strain rosettes in relation to the instrument hut at *Fram 3;* (*b*) Portion of time series data obtained from one of the strain meter rosettes at *Fram 3;* (*c*) Expanded section of *b*.

Finally, a suite of atmospheric measurements were made. They included continuous recordings of temperature, atmospheric pressure, wind direction at 2 m, and wind speeds at 2 m and 10 m. The data will be correlated with changes observed with the oceanographic measurements. They will also be used in conjunction with geostrophic wind estimated from buoys, to determine geostrophic drag laws appropriate for the region.

In addition to their other projects, a thermistor chain was installed for the study of internal waves. Preliminary results suggest the presence of an active internal wave field.

Scott Polar Research Institute

Ice strain and wave propagation. The purpose of this experiment was to measure the directional energy spectrum and velocity of propagation of flexural gravity waves in the ice cover of the Arctic Ocean, using three rosettes of three strain meters, each in a triangular array, and the attenuation rate of the waves by simultaneous recording from three-strain meter rosettes, two being retained at the main camp and the third being taken to a helicopter-established camp some tens of kilometers away.

For the first experiment an existing hut at the main camp was used as an instrument hut, and three rosettes of strain meters were set up as shown in Figure 5. Each rosette consisted of three wire strain meters of high sensitivity (better than 10^{-8} strain) and rugged design evolved at SPRI for this purpose [*Moore and Wadhams*, 1980]. The strain-sensing element was a 1-m long Invar wire. Each instrument was frozen into the ice and protected by a wooden box, which was placed over it. Snow was then shoveled over each box to reduce thermal drift.

Data were recorded on digital and FM analog tapes at times when radio interference was least, i.e., at night or when there was no flying between Nord and *Fram 3*. Recording went on for 4 weeks during April–May 1981, and about 150 hours of data were recorded.

Ice thickness was measured at the strain meter sites. Other data needed for interpretation of the results and recorded by other investigators on *Fram 3* were wind speed and direction (continuously), floe rotation (daily, usually only about 1° per day), and internal wave activity (by J. Morison using thermistor chain).

During the second project, three attenuation experiments were carried out by deploying a fourth strain meter rosette away from the main camp. Positions of these remote sites relative to the main camp were 93 km north, 46 km south, and 139 km north. Each remote rosette was set up with its axes aligned as closely as possible with those at the main camp. At each remote site, at least 1 hour of data was recorded concurrently with recording at the main site.

Part *b* of Figure 5 shows a typical length of record from three strain meters in a single rosette. It is immediately apparent that there are two distinct components of oscillation present. The short-period oscillations have a typical amplitude of 10^{-7} strain and period of 30 s. An expansion of the time scale (Figure 5*c*) shows that oscillations from the three strain meters are in phase. This suggests that they are flexural gravity waves, as recorded on previous occasions in the Arctic Ocean [*Hunkins*, 1962; *LeSchack and Haubrich*, 1964]. The ice thickness at the site was 3.2 m, from which we can infer that the wave amplitude was about 3 mm. Long waves of this kind can be explained as being the envelopes of wave packets found in the open sea [*Larsen*, 1978*a*, *b*]. The Arctic Ocean ice cover, however, acts as a filter, which removes all shorter-period components by scattering or creep mechanisms. Full analysis of the results will reveal whether this is really the case, since it will give the directional spectrum of the waves (to show whether they are coming from the nearest open ocean in Fram Strait), any correlation with local wind (in case direct generation through the ice is occurring), and the attenuation rate.

The long-period oscillations apparent in Figure 5*b* were unexpected. They are of greater amplitude than the short-period oscillations—typically 5×10^{-7} strain—and have periods of about 10 min. This is far too long for any flexural gravity wave, especially since it implies a very large vertical amplitude of ice oscillation. Furthermore, on the expanded scale (Figure 5*c*), and on Figure 5*b*, it can be seen that two strain meters are in phase while the third is in antiphase. This is the result that we would expect from a wave of compression passing through the ice, i.e., a longitudinal wave. Our interpretation is that (1) the ice is responding to the presence of internal waves, concurrently measured by J. Morison and found to have a typical period of 10 min or (2) the ice is responding to the very small variations in sea surface elevation associated with the internal waves.

On April 10 the long-period strain field increased greatly in amplitude some 24 hours after the onset of a 12 m/s wind. If it is true that ice acceleration generates internal waves through interaction with pressure ridge keels, then we would expect increased long-period ice strain to follow a storm. Further analysis of the joint data sets will determine whether this hypothesis is valid.

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Greenland Air Charter. Helge Siljuberg and Goren Lindmark (Bell 204 pilot and mechanic).

Bradley Air Service. Ross Michelin, Bill Smith and Gary Moore (*Fram 3* Twin Otter crew).

Polar Research Lab. Jim Aikens, Don McWilliams and Chris Hutton (Tri-Turbo crew).

Acknowledgment

This work was supported by the Office of Naval Research under contract N00014-76-C-0004 and by the National Science Foundation under grant DPP-8025744 to the Bigelow Laboratory.

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MIZEX - International Marginal Ice Zone Experiment investigates interaction of arctic sea ice, ocean and climate. Lamont Newsletter 6, Spring 1984.

MIZEX: International Marginal Ice Zone Experiment Investigates Interaction of Arctic Sea Ice, Ocean and Climate

In summer the central Arctic Ocean is covered with a mosaic of ice floes about 3 m in thickness and ranging up to several km in width. In winter, sea ice extends far beyond the limits of this perennial pack covering the entire Arctic Ocean, including the shelf seas, and reaching into the Bering Sea and Canadian Archipelago. The ice of this seasonal winter extension attains one to two meters in thickness (see Figure). Ice extent varies also on scales other than seasonal, with fluctuations varying in length from hours and days to the ice-age variations extending over millenia.

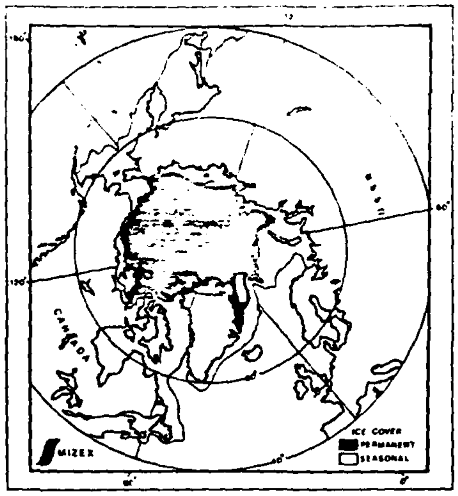
When observed from above, the open ocean is dark in color, while sea ice, when covered with snow, is white. The albedo (fraction of light reflected) is about 0.1 for the open sea and about 0.8 for snow-covered sea ice. This large contrast in albedos leads to strong contrast in radiation budgets between ice and open water, which relates directly to the heat budget over the ocean.

The fundamental question is how sea ice relates to weather and climate. There is clearly a close relationship, but it is not clear to what degree sea ice is a passive result of other climatic influences and to what degree it is an active element which is capable of itself interacting with ocean and atmosphere to produce effects which are not presently predictable. A number of ways in which ice, air and water interact have been identified, but their relative importance is not known.

The actual dividing line between sea ice and open ocean, the ice edge, should be the most sensitive area to influences that control ice extent, and it is the region which has been chosen for study. The location of the edge of the ice pack depends upon the action of winds and currents, as well as on the heat budget. These factors are not straightforward since there is an interaction of air, sea and ice with each other in various feedback loops. For example, when the ocean freezes, albedo increases sharply, and short-wave radiation, which has been warming the water, is reflected, thus intensifying the cooling effect in a positive feedback. Another positive feedback occurs when ice melts, stratifying the ocean with a surface layer of low salinity. The stratification inhibits vertical mixing and heat loss, thus slowing the rate of melting.

An understanding of these and other physical processes needs to be based on actual observations of ice edge changes. Such observations are essential for the design of models designed to reproduce these processes, making it possible to predict changes in ice edge location. The Lamont Arctic Group under Ken Hunkins took part last year in a pilot project, MIZEX 83 (Marginal Ice Zone Experiment), for a large-scale field experiment now underway on the ice margin between Greenland and Spitsbergen (see Figure).

Seven ships and an equal number of aircraft are involved in the international MIZEX project. In addition to the U.S. effort (sponsored by ONR), there is participation by the Federal Republic of Germany, Norway, Canada, France, Great Britain and Denmark, with each nation contributing to the scientific effort, as well as to ship and aircraft support in some cases. The ice margin in Fram Strait between Greenland and Svalbard may be characterized as "advective," dominated by ocean currents and wind, rather than by heat budget. In this region, sea ice from the Arctic Ocean is carried far south into the Atlantic by the cold, low-salinity East Greenland Current on the west side of the Strait. On the east side, the warm high-salinity West Spitsbergen Current keeps the



The maximum and minimum extent of sea ice in the Northern Hemisphere.

coast nearly ice free throughout the year. The ocean in the Greenland Sea marginal ice zone is dominated by permanent and transient frontal systems, by eddies and by upwelling along the ice edge. Vertical fine structure (10 m) and mesoscale (100 m) structures formed by interleaving of Polar and Atlantic Water intrusions are also frequently observed.

These features are unique to the ocean in marginal ice zones and must interact with the ice and atmosphere. During summer for example, the front along the ice edge is intensified by meltwater input. Another interaction occurs when ocean eddies carry ice across the marginal ice zone into warmer water where it melts. In still another interaction, the strong stratification resulting from summer meltwater reduces vertical mixing momentum and reduces the drag coefficient between ice and water so that floes drift faster given the same wind stress to drive them. We need to know the relative importance of these and other interactions in controlling the location of the ice edge.

The MIZEX program includes a drifting phase with an array of instruments deployed on the ice to monitor the ice motion, meterology and upper ocean conditions. This instrument array is set and maintained by icebreaking ships which also spend part of their time drifting with the ice. Helicopters from these ships are used for carrying out oceanographic surveys over the ice-covered part of the marginal ice zone. A portable CSTD profiler, developed by Ocean Data Systems, has been modified and improved by the Lamont group for these helicopter surveys. At landing sites, a small hole is made through the ice, or a natural opening is used, and the sensor probe is lowered to 500 m, using a special winch mounted in the helicopter. The objective is to make an oceanographic survey and to map features beneath the ice cover. During MIZEX 83, profiles were made at 120 sites by Lamont oceanographers Tom Manley and Jay Ardai, using two helicopters based primarily on the Norwegian M/V POLARBJORN, with some flying also from the Norwegian R/V LANCE and FRG icebreaker, POLARSTERN. These helicopter surveys are closely coordinated with CTD surveys by oceanographers from the University of Bergen carrying out surveys in open water. The helicopter and ship results are combined to give synoptic views of oceanographic structure across the entire marginal ice zone, both open and covered. During MIZEX 83, a mesoscale ocean eddy about 50 km was tracked as it drifted southward beneath the ice at a rate of 7 km per day over a 5-day period. Such eddies can provide an efficient exchange of temperature and salt across the ice margin, which can affect its location.

An array of moored oceanographic instruments forms the other part of Lamont's MIZEX program. Four subsurface moorings equipped with current, temperature and conductivity recorders were deployed in 2,400 m water depths near the center of Fram Strait to monitor mesoscale oceanographic features over a time period of six weeks. During MIZEX 83, mean currents near the center of the Strait in open water near the ice edge were southward, suggesting the presence of a large, deep gyre which recirculates the entire water column in this area. In addition, a shallow surface cold eddy was observed to drift across the array. This eddy, which was only about 100 m deep, was evidently shed from the ice edge and provides another example of eddies mixing temperature and salinity across the ice margin. Surveys and statistics covering a number of these eddies are still needed to assess their quantitative importance.

For MIZEX 84, Lamont will have a similar program of helicopter-CSTD surveys and oceanographic moorings. As the results are analyzed, simple physical models are being developed to interpret the observed features. A conceptual model of ice export through Fram Strait has been developed, which emphasizes the importance of the West Spitsbergen Current in melting ice on the east side. Ice is driven southward by wind across the entire Strait. On the Greenland side, the water is cold, no melting occurs and ice is carried far south. On the Svalbard side, ice melts as it encounters the warm waters flowing north. The implications of this model are being explored with budget studies based on MIZEX results.

Finally, studies have begun on numerical models of the ice edge using a simplified ice-air-ocean system. The plan is to test some of the feedback mechanisms between ice, air and water which were mentioned earlier. When these mechanisms are effectively modeled and understood, their effects will be incorporated in a global atmospheric-ocean circulation model (GCM). So far GCMs, which are used for climatic modeling and prediction, incorporate sea ice only in a rudimentary way. It should be possible, as a result of the field and numerical experiments described, to better understand the physical processes along the ice edge, so that the most important ones can be introduced into a GCM for improved climatic forecasting, which includes the important factor of sea ice in a more realistic way.

Southern Ocean

(continued from opposite page)

melting or growth and other parameters at the ice shelf base. At regular intervals, data would be telemetered via Argos satellite to institutions in the U.S.

The polar regions offer a challenge of a scientific and personal nature. As the significance of the ice to large scale climate patterns and variability becomes more apparent, there will be more ambitious attempts to gather the data necessary to assess this influence, resolve the relevant processes and develop effective polar inputs to climate models. Lamont oceanographers are particularly active in this quest.

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